

Evaluating the Impact of Interventions on Network Capacity

by

Sujith Reddy Rapolu

Bachelor of Technology in Civil Engineering
Indian Institute of Technology, Roorkee, India (2008)

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degree of

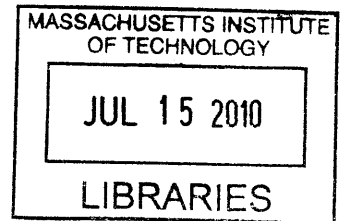
Master of Science in Transportation

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2010

ARCHIVES



© 2010 Massachusetts Institute of Technology. All rights reserved.

Author _____
Department of Civil and Environmental Engineering
March 25, 2010

Certified by _____
Moshe E. Ben-Akiva
Edmund K. Turner Professor of Civil and Environmental Engineering
Thesis Supervisor

Certified by _____
Charisma Farheen Choudhury
Assistant Professor, Department of Civil Engineering
Bangladesh University of Engineering and Technology
Thesis Co-Supervisor

Accepted by _____
Daniele Veneziano
Chairman, Departmental Committee for Graduate Students

Evaluating the Impact of Interventions on Network Capacity

by

Sujith Reddy Rapolu

Submitted to the Department of Civil and Environmental Engineering
On March 25, 2010 in partial fulfillment of the requirements for the degree of
Master of Science in Transportation

Abstract

Analyzing the capacity impact of different diverse interventions on the network is essential in understanding the causes of congestion. In this thesis, a framework to understand the effects of different disruption events and activities on the network has been presented. A common unit, independent of network and type of intervention, has been used in this regard. Expressing the capacity impacts on this common unit (referred to as 'common capacity currency' in this thesis) will be useful in assessing the relative scale or intensity of the different types of interventions across networks of different size and traffic flow levels.

A network from central London, U.K. has been used to quantify the capacity impact of interventions. The network, located near Victoria station area of London, is a complex and dense urban network within the congestion charging zone.

MITSIMLab, a microscopic traffic simulation laboratory developed for evaluating different traffic management systems has been used for the purpose of capacity analysis. To measure the capacity of a network in MITSIMLab, the network is flooded with vehicles by scaling the origin-destination (OD) matrix. The network is assumed to reach its capacity when pre-trip queues start forming that is no further vehicles can be loaded in the network. The total distance travelled by all the vehicles in one hour when the network has reached its capacity are noted and converted to passenger-car-unit (PCU)-km per hour. The average speeds of the vehicles at capacity are also compared.

To understand the impact of interventions on network capacity, street-works and illegally parked vehicles are simulated at different levels of complexity. The common capacity currencies (PCU-km per hour) are compared with the base case which didn't include any interventions.

The results of the capacity analysis predicted a drop in network capacities and average speeds under different scenarios correctly as expected. Street-works resulted in a greater drop in network capacity and average speed than a near-side lane disruption. Further, among the scenarios tested for near side lane disruptions, a 1 minute disruption every 3 minutes caused the greatest reduction in network capacity and average speed.

Thesis Supervisor: **Moshe E. Ben-Akiva**

Title: Edmund K. Turner Professor of Civil and Environmental Engineering

Thesis Co-Supervisor: **Charisma Farheen Choudhury**

Title: Assistant Professor, Department of Civil Engineering

Bangladesh University of Engineering and Technology

Acknowledgements

I would like to thank my advisor Prof. Moshe Ben-Akiva, for his faith in me. His sheer brilliance was highly inspiring. I would also take this opportunity to express my sincere gratitude to my co-advisor Dr. Charisma Choudhury for guiding me at each and every stage of my work in the lab. Her motivation and support were the most valuable during my stay at MIT.

This research is funded by Transport for London (TfL) as part of its collaboration with MIT. I would like to acknowledge Andy Emmonds and Jonathan Turner of TfL for the support they have lent to this project, as well as the staff of Road Network Performance and Research and Inventory for Network Capacity and Activity – Amitabh Bose, Alistair Davis, Katherine Blair, Allison Cowie and Andrew Wallace for their assistance and feedback. Thanks to Emmet Ruxton and Vladimir Vorotovic for their help with the VISSIM models.

I would also like to thank Dr. George Kocur for agreeing to guide me through the final six units of course-work during the most crucial phase of my stay at MIT. Thanks to Patty Glidden, Kris Kipp and Jeanette Marchocki for helping me with the administrative processes.

I am extremely grateful to all my friends at the ITS lab for being so helpful. I would like to thank Enyang Huang and Dr. Yang Wen, Oracle Corp. for their help in solving the issues with Linux and MITSIMLab source code. Thanks to Li Qu for her tremendous help in making me understand the finer aspects of MITSIMLab. I would also like to acknowledge the friendship and support of my other friends in CEE: Zheng Wei, Anwar Ghauche, Varun Ramanujam, Vikrant Vaze, Sarvee Diwan, Cristian Angelo Guevara, Swapnil Rajiwade. Thanks to Tina Xue for making the lab a vibrant and lively place.

I would like to thank Chaithanya Bandi from the bottom of my heart for his inspirational thoughts and perspective on virtually every topic and for his constant help. Thanks also to Nitish Umang for his encouragement during the stressful times. I would like to thank all my friends at MIT for making my stay a thoroughly enjoyable experience. I would also like to express my gratitude towards Mahender Mandala for always being there in every good and bad experience.

Above all, I thank my family: my parents and my sister, for their love and unending support.

Table of Contents

Abstract	3
Acknowledgements	5
Table of Contents	7
List of Tables	9
List of Figures	11
1. Introduction	13
1.1 Motivation	13
1.2 Thesis Contributions	15
1.3 Thesis Outline.....	16
2. Literature Review	17
2.1 Capacity Analysis using Empirical Methods	17
2.2 Analyzing capacity using simulation approach.....	19
2.3 Summary	28
3. Methodology	29
3.1 Network Capacity	29
3.2 Modeling Framework.....	31
3.2.1 MITSIMLab.....	31
3.2.2 Calibration Framework.....	34
3.2.3 Goodness-of-fit measures	37
3.2.4 Measuring Network Capacity	39
3.3 Summary	43

4. Case Study – Victoria Network	45
4.1 Dataset description.....	45
4.1.1 Study area	45
4.1.2 Dataset overview.....	47
4.2 Aggregate Calibration.....	49
4.3 Aggregate Validation.....	52
4.4 Base Capacity	53
4.5 Scenario Analysis	54
4.5.1 Long Term Street-works	54
4.5.2 Near-side lane disruptions	61
4.6 Summary	67
5. Conclusion	69
5.1 Thesis summary.....	69
5.2 Contributions	71
5.3 Directions for Future Research.....	72
Appendix A: Detailed Results of A2 Network	75
A.1 Long Term Street-works	75
A.2 Near-side lane disruptions	81
Bibliography	87

List of Tables

Table 2.1: Value of Time for each vehicle type	22
Table 2.2: Total cost saving (£ per 1000 vehicles)	26
Table 2.3: Total cost saving (£ per 1000 trips)	27
Table 3.1: Successive iterations for the scaling factor of an OD matrix.....	42
Table 3.2: Successive iterations for the scaling factor of an OD matrix.....	43
Table 4.1: Statistics of calibration and validation data.....	49
Table 4.2: Calibration results.....	51
Table 4.3: Goodness of fit statistics for traffic speed comparison.....	51
Table 4.4: Corrected Goodness of fit statistics for traffic speed comparison.....	52
Table 4.5: MOEs for speeds.....	53
Table 4.6: Corrected MOEs for speeds.....	53
Table 4.7: Street-works – Network Capacity values.....	57
Table 4.8: Street-works – Impact on average speed across the whole network.....	58
Table 4.9: Combination of Street-works – Network capacity values.....	60
Table 4.10: Combination of Street-works – Impact on average speed across the whole network	61
Table 4.11: Near side lane disruptions – Network Capacity values.....	63
Table 4.12: Near side lane disruptions – Reduction in network capacity.....	65
Table 4.13: Near side lane disruptions – Impact on average speed across the whole network.....	66
Table A.1: Street-works average speed summary (mph)	77
Table A.2: Street-works speed impact summary.....	77
Table A.3: Economic corridor analysis of street-works tests (£ per 1,000 vehicles)	78
Table A.4: Economic corridor analysis of street-works tests (£ per 1,000 trips)	79
Table A.5: Average Journey Time (sec) for street-works 1 and 2.....	79
Table A.6: Average Journey time (sec) for street-work 3.....	80
Table A.7: Average Journey time (sec) for street-work 4.....	81
Table A.8: Near side road disruption coefficient of variation.....	83

Table A.9: Near side road disruptions - speed impact (mph)	83
Table A.10: Nearside disruption economic analysis (£ per 1,000 vehicles)	84
Table A.11: Nearside disruption economic analysis (£ per 1,000 trips)	85
Table A.12: Nearside road disruption average speed per section (mph)	85

List of Figures

Figure 3.1: Hypothetical network with two links	30
Figure 3.2: Elements of MITSIMLab and their interactions	32
Figure 3.3: Calibration and validation framework.....	34
Figure 3.4: Framework for measuring network capacity	40
Figure 4.1: Network Description	46
Figure 4.2: Network as seen in MITSIMLab.....	47
Figure 4.3: Location of sensors.....	48
Figure 4.4: Victoria Network – Location of Street-work 1	55
Figure 4.5: Victoria Network - Location of Street-work 2.....	55
Figure 4.6: Victoria Network- Location of Street-work 3.....	56
Figure 4.7: Victoria Network – Location of Street-work 4	56
Figure 4.8: Street-works - Network Capacity.....	57
Figure 4.9: Street-works – Impact on speed	58
Figure 4.10: Street-works – Capacity v/s Speed	59
Figure 4.11: Victoria Network - Locations of near-side lane disruptions	63
Figure 4.12: Near side lane disruptions - Network Capacity.....	64
Figure 4.13: Near side lane disruptions - Network Capacity comparison.....	65
Figure 4.14: Near side lane disruptions – Impact on speed	66
Figure A.1: Street-works locations on the network	75
Figure A.2: Journey time sections as surveyed.....	76

Chapter 1

Introduction

1.1 Motivation

Traffic congestion is a major problem in all the major cities around the world. According to the 2009 Urban Mobility Report (Schrank and Lomax 2009), in 2007, congestion caused urban Americans to travel 4.2 billion hours more and to purchase an extra 2.8 billion gallons of fuel for a congestion cost of \$87.2 billion – an increase of more than 50% over the previous decade. Further, with the rapid growth of population and car ownership, there is tremendous pressure on the existing roads, thereby worsening the problem of traffic congestion. Therefore, addressing this problem has been a major transportation priority in all the major cities.

City planning and urban design practices can have a huge impact on the levels of future traffic congestion. Congestion can also be reduced by either increasing the road capacity or by reducing traffic demand. Road capacity can be increased by building new roads or through traffic management improvements. Traffic demand can be reduced through The strategies of this type include flexible work schedules (that allow employees to travel off-peak), transit-oriented regional development, community-based car-sharing etc. as well as restrictive measures such as parking restrictions, road and congestion pricing etc..

Congestion pricing is a system of charging users of a transportation network in periods of peak demand to reduce traffic congestion. This has been applied on urban roads in cities like London, Stockholm, Singapore etc. In London, a fee of £8 is charged on some vehicles for each day the vehicle enters or travels within certain parts of London designated as the Congestion Charging Zone (CCZ).

According to the sixth annual impacts monitoring report (Transport for London, 2008) on central London congestion charging, 2003 and 2004 - the years immediately following the introduction of the original scheme - saw average reductions in congestion of 30 percent against the representative 2002 baseline. Further, the level of traffic of all vehicle types entering the central Congestion Charge Zone was now consistently 16% lower in 2006 than the pre-charge levels in 2002 (Transport for London, 2007). Also, the congestion charge brought in an annual operating net income of £89.1m for TfL during the financial year 2006/07 (Transport for London, 2007).

But, recent measurements of congestion have indicated that conditions are deteriorating. Data from the congestion charging monitoring programme in central London indicate a substantial loss of charging-related decongestion benefits over the last 18 months within the original charging zone. The average reduction for the 2005 calendar year was 22 percent, lower than 2003/04. 2006 and 2007 however saw accelerating loss of the original congestion benefits. Average congestion in 2006 was just 8 percent below pre charging levels. Average congestion in 2007 was identical to representative pre charging values. This is in spite of sustained reduction in the volume of traffic circulating within the original charging zone (Transport for London, 2008).

The conventionally-assumed relationship between traffic volumes and delay appears to have reversed: in recent years, *falling* traffic has been associated with *increased* delay. This firmly points to a reduction in effective network capacity.

There can be a number of reasons for the loss of effective capacity. Some of them are change in vehicle traffic fleet composition, increase in the number and length of bus and cycle lanes, increase in the number of advanced stop lines at traffic signals, increase in the number of non-recurrent congestion causes like street-works and incidents, increase in the number of traffic signals and pedestrian crossings and mode shift to buses, cycles and other modes of public transport. Further, these interventions may or may not have similar impacts across different networks. However, there is little in the way of direct causal evidence to substantiate this hypothesis and, seemingly, no established framework

for expressing the capacity impact – and hence the congestion impact – of the many diverse interventions in a network as well as across networks.

This has motivated the attempt to establish a common capacity currency and a quantitative framework to understand these effects and to arbitrate more rationally between them. Is it ‘better’ to devote network capacity to contributing to fewer people killed in road traffic accidents, or to providing faster and more reliable journeys to, for example, freight and servicing trips? Is the combined impact of several different interventions greater than the sum of their individual impact; do they interact in a compounding way? To answer these questions, there is a need for a framework that can account for road capacities at link, junction and network level.

1.2 Thesis Contributions

The main contribution of this thesis is the development of a framework that can account for road capacities at a network level. This has been done by establishing a common currency so that the impact of different activities can be compared across scenarios.

In this research, we propose to measure network capacity in terms of vehicle-km per hour. This is the total distance traveled by all the vehicles that can be accommodated in the network over a period of one hour. It is important to associate the average speed of the vehicles with this measure of network capacity to better understand the impact of various interventions on the network.

We propose a simulation framework using a microscopic traffic simulator, MITSIMLab (Yang and Koutsopoulos, 1996) to measure the capacity of a network with and without interventions. The theoretical capacity of the network can be obtained by flooding the model i.e. by scaling the O-D matrix. The maximum number of vehicles which can be accommodated in the network (i.e. can be loaded in the network before pre-trip queues start forming) is defined as the capacity of a network. To the best of our knowledge, this

is the first time where the flooding approach (increasing the traffic demand) has been used to analyze the capacity at a network level.

The framework developed is applied to a network from London, U.K. to evaluate the impact of street-works and near side lane disruptions on the network. Using the calibrated model, capacity analysis is done for different locations of street-works and near-side lane disruptions.

1.3 Thesis Outline

The remainder of the thesis is organized as follows. A review of the literature on network capacity is presented in Chapter 2. The modeling methodology and framework to measure network capacity is detailed in Chapter 3. Chapter 4 is a case-study of a network from the city of London, U.K. where MITSIMLab, a microscopic traffic simulation laboratory developed for evaluating different traffic management systems, is calibrated and capacity analysis done using the frame-work mentioned in chapter 3 to evaluate the impact of street-works and near side lane disruptions on network capacity. Finally, the thesis summary and directions for future research are discussed in Chapter 5.

Chapter 2

Literature Review

This chapter is presented in two parts: the first section reviews the work done to estimate road traffic capacity using empirical methods. The second section details studies focusing on capacity analysis using simulation tools.

2.1 Capacity Analysis using Empirical Methods

The Highway Capacity Manual (TRB 2000) provides the traditional basis for a standardized analysis of road traffic qualities. It contains concepts, guidelines, and computational procedures for computing the capacity and quality of service of various highway facilities, including freeways, highways, arterial roads, roundabouts, signalized and unsignalized intersections, rural highways, and the effects of mass transit, pedestrians, and bicycles on the performance of these systems. Traffic quality is classified into six “levels of service” (LOS) which are denoted by the letters A (free flow traffic) through F (congested). The LOS concept as it is currently used is strictly bound to a short interval evaluation period (e.g., 1 hour). LOS classifications are based on one or more “measure of effectiveness” (MOE), such as average travel velocity. The MOEs incorporate the decisive aspects of traffic quality. Usually there is no objective way to determine the threshold MOE values used to define a particular LOS. A more rational manner of derivation would be desirable, especially to discriminate between the higher LOS like D (sufficient) to E (capacity) to F (oversaturation) (Brilon, 2000).

Geistefeldt (2008) compared the stochastic capacities with conventional capacity values. Conventional design capacities given in guidelines like the HCM (TRB, 2000) or the German HBS (FGSV, 2001) are based on the analysis of speed-flow diagrams. The

volume at the apex of the speed-flow relationship is treated as the capacity of the facility. In contrast, methods for stochastic capacity analysis deliver a capacity distribution function, which represents the probability of a traffic breakdown in dependence on the flow rate. For a considerable number of data samples from freeway sections in Germany, the breakdown probability that corresponds to the capacity obtained from the speed-flow diagram was determined. Compared to the impact of speed differences in fluid traffic, a traffic breakdown entails significant delays for the users of a freeway. Hence, the researcher proposes that the breakdown probability be used as an important measure of effectiveness, because it represents the reliability of traffic operation. Defining a maximum acceptable breakdown probability could therefore be considered as an alternative way to derive design capacities.

Hyde and Wright (1986) proposed two extreme value methods to estimate road traffic capacity. The researchers gave consideration to the variations in flow which occur over a time during normal traffic conditions, and to the characteristics of the extreme values which occur from time to time under these conditions. Two distinct types of statistical theory can be applied to extreme values. First, one can apply straightforward probability theory, to predict the largest flows likely to be observed during a given period, assuming an idealized traffic stream with a known flow counting distribution. Second, one can attempt to deduce an upper limit from observed flow data using asymptotic methods of the kind which are frequently used in connection with meteorological and flood defense problems. Both methods were applied to a sample of 9000 flow values recorded at a site in London. Both methods showed a reasonable fit to the data, but only the asymptotic method reveals a clear upper limit. The drawback is that it might be difficult in applying these methods under specific intervention scenarios, particularly in attributing the loss of capacity whenever an incident occurs on the road.

Minderhoud et al. (1997) studied the empirical capacity estimation for uninterrupted roadway sections. Headways, traffic volumes, speed, and density are traffic data types used to identify four groups of capacity estimation methods. Aspects such as data requirement, location choice, and observation period were investigated for each method.

Among the methods studied were the headway distribution approaches, the bimodal distribution method, the selected maxima, and the direct probability method. Of the methods based on traffic volume counts, the researchers recommend the product limit method for practical application because of sound underlying theory. Attempts to determine the validity of existing roadway capacity estimation methods were disappointing because of the many ambiguities related to the derived capacity values and distributions. Lack of a clear definition of the notion of capacity is the main hindrance in understanding what exactly represents the estimated capacity value or distribution in the various methods. If this deficiency is corrected, promising methods for practical use in traffic engineering are the product limit method, the empirical distribution method, and the well-known fundamental diagram method, in that order.

Overall, though research has been done on analyzing capacity using other indicators like speed and density, there has not been much study in capacity prediction, particularly on quantifying the capacity impact of interventions on the overall network. The next section discusses the work done to analyze capacity using simulation. Results from a case-study in London are also presented. The work discussed in the next section is closely related to the work done in this thesis.

2.2 Analyzing capacity using simulation approach

There have been several studies mentioned in the literature where capacity was analyzed through the use of simulation tools. Sinha et al. (2007) examined the modeling of incidents in microscopic simulation models and the effects of calibration parameters on the simulated reductions in capacity due to incidents. It is essential that simulation programs be able to model correctly the reductions in highway capacity due to incidents and the lane changing behaviors of drivers ahead of incident locations. The researchers simulated a basic freeway segment using three widely used microscopic simulation models – CORSIM (FHWA 2006), VISSIM (PTV 2009), and AIMSUN (Transportation Simulation Systems 2009). Calibration parameters of the three models were varied to

determine if it is possible to calibrate the models to achieve target link capacity values for both incident and no incident conditions. The target capacity values used in the investigation were those presented in the HCM 2000. It was found that there is a need to calibrate model parameters in all the three models to produce acceptable reductions in capacities due to incidents. Further, there is a need to introduce incident-specific time-variant calibration parameters in AIMSUN and VISSIM. In this study, the capacity of a link in a simulation model was defined as the throughput in vehicles per hour that can pass through the link when there is enough traffic demand to reach this capacity. The traffic demand volume in the simulation model was increased until the throughput reaches its maximum value. This maximum value was then considered as the link capacity. Jha (1998) also varied the demand in his simulation experiments around capacity for the analysis of the impact of freeway bottlenecks. Also, Jha and Bierlaire (1998) studied the reduction in throughput due to a bottleneck at a freeway merging section in a simulation framework by fixing the main-line demand and varying the on-ramp demand. However, this study was also limited to a link level and not tested at a network level.

Minderhoud and Bovy (1999) conducted a simulation study to assess the effect of an (autonomous) intelligent cruise control (ICC) on the traffic-flow characteristics on motorways. Ten different ICC designs are investigated and compared with a reference situation without such support systems. A capacity analysis was performed for a common bottleneck situation: an on-ramp to a two-lane motorway. On the basis of the simulation results, some unexpected findings emerged. Support systems that support the driver at all speeds and that do not restrict the deceleration level give rise to capacity gains of about 12 percent. However, the first-generation ICC systems will hardly increase traffic-flow performance. A special stop-and-go ICC design did not improve the traffic-flow quality. It was found that, regardless of the ICC type, a headway setting of 1.2 s did not change roadway capacity near an on-ramp bottleneck significantly.

In London, a study was carried out to assess the impact of typical network changes on traffic capacity. The work done in this study is closely related to the work done in the

thesis. Hence the results of this study are presented in detail. A VISSIM micro-simulation model based on a section of the A2 road was chosen for this study. The material presented in the subsequent part of this section is based on the report for Transport for London (TfL) titled “Impact of Interventions on Road Capacity in London”, 2009.

In this study, the following six different scenarios were tested:

- A change in speed limit
- Mode shift
- Bus and cyclist interactions
- Long term street-works
- Nearside lane disruptions (temporary parking)
- Pedestrian facilities

Each test conducted in this study was reported moving from a ‘macro’ to ‘micro’ scale. The three scales considered were: the network, the corridor, the sections. The ‘network’ includes the entire VISSIM network, including side roads and the sections of the main corridor beyond the edge of the surveyed sections. This scale of analysis enables the usage of network wide default statistics which are more reliable than the aggregation of recorded localized statistics. The ‘corridor’ corresponds to the sections of the network for which journey time surveys were carried out. The ‘sections’ correspond to the initial sections of the journey time surveys. These smaller elements of the network enable a more refined analysis, which is particularly useful for the local intervention tests.

The first three tests - change in speed limit, mode shift and bus and cyclist interaction - relate to network-wide changes. The next three tests - long term street-works, nearside road disruptions, pedestrian facilities - correspond to more localized interventions or disruptions. In order to evaluate the impact of interventions at different levels of saturation, the trip matrix was adjusted by a uniform factor.

The study identified the impact, both in terms of traffic speed and the resulting change in economic cost to road users, of the interventions listed above. The approach taken was to model the changes in journey time by mode (car, LGV, HGV, bus, motorcycle and cycle)

and to apply a value of time in line with values provided by TfL in the Business Case Development Manual (BCDM). Due to the possibility of differences in vehicle numbers between base and test scenarios (e.g. due to off-network queuing), the same level of vehicle flow for the base/test comparison was assumed in each case, so that the effect of the journey time change can be evaluated i.e. a fixed-trip matrix was used. The 2007 values of time were used; these are shown in Table 2.1. They have been expressed as values of time per vehicle, so average vehicle occupancy has been taken into account.

Table 2.1: Value of Time for each vehicle type

Vehicle Type	Value of Time (£ /hr)
Car	14.62
LGV	16.98
HGV	14.89
Bus	125.16
Motorcycle	8.27
Pedestrian	5.23
Cycle	6.59

The economic analysis was carried out at the corridor and section scales only, as the network outside the corridor was not validated against journey time surveys and entry links to the network are not regarded as necessarily representative of network conditions. (In respect of the latter, the arrival flow profile might not be in accordance with street conditions and the upstream junctions are simply not represented).

A summary of the results under each intervention scenario is presented in the rest of this section.

Change in speed limits

The results from the comparison of a change in speed limit between 30mph and 20mph are:

- The average speed across the network is lower than the speed limit, so the impact of any change is therefore likely to be small
- Vehicles spend 20% of their time above 20mph in the base case scenario with a 30mph speed limit
- Saturated conditions result in an increase in traffic flow instability
- The impact on the average speed of the 30mph to 20mph speed limit change is a reduction in average speed of between 11 and 12% i.e. (11.1mph to 10.0mph at 85% saturation)
- Vehicles have a smoother progression with less time queuing with a lower speed limit.

Mode shift

A proportionate transfer of trips from car to bus, to cycle (and to both) was tested; the characteristics of the base mode share is therefore relevant to the analysis – in the model area bus use accounts for around 25% of person trips, and the impacts of this test are greater than for a shift to cycling, which has a lower local mode share. At current demand levels, the shift to bus or cycle results in a speed increase of between 11% and 57%; at higher demand levels a lower benefit is observed.

Some detailed observations regarding the mode shift comparison are as follows:

- The two key implications of mode shift for traffic network capacity (and stability) are (1) the effects it has on traffic volume and therefore network saturation, and (2) the interaction between these vehicles within and across lanes – an issue of network efficiency. The shift in traffic conditions (saturation) resulting from changes in mode has the greatest impact. A mode shift which moves the network conditions from saturated to fully over saturate generates additional instability in a single section of the network and makes it difficult to draw wider conclusions. On the other hand, a drop in traffic large enough to create free flowing network conditions has a greater impact than that generated by the operations of an individual transport mode.

- The increase in cyclist volumes has less operational impact on other users when the rest of the network is busy, although in all cases there is an impact on bus operations in bus lanes since buses experience difficulties in overtaking cyclists.
- Setting aside capacity issues, a mode shift that results in fewer vehicles in total is likely to be beneficial since, at least in modeling terms, the greater the interaction between vehicles, the greater is likely to be the variation in network traffic speed from one run to the next.
- Increasing bus volumes has a negative economic impact on general traffic journey time at a low level of mode shift; at the higher level tested, there is a positive economic impact.

Bus & bicycle interactions

This test assesses the impact of increasing the volume of cyclists in the bus lanes. The rest of the general traffic remains the same and therefore this test is not directly comparable to the other tests performed for this study. The results from the bus and cycle interaction test in bus lanes show that:

- In unsaturated conditions, the increase in cycle volumes has a limited impact on other modes' speed, but buses are affected.
- Cyclists 'jump' the queues and therefore can generate major delays to other vehicles on narrow and congested stretches of road.

Long term street-works

The results from the long-term 80m street-work comparison show that impact can be significant depending on the intervention location. This depends on:

- The existing saturation level and the future saturation level at that location
- Whether the street-works merely shifts traffic management features (e.g. a merge) from an existing 'normal' merge to an upstream 'street-works' merge, or is a 'new' intervention.

However for the network tested, the effect of any individual intervention is minimal at a network level, provided such an intervention does not make the individual location oversaturated. However when a number of street-works take place at the same time in the same area, they have a combined effect markedly greater than the sum of the individual interventions.

Nearside lane disruption

The nearside lane disruption shows that:

- A 20 minute parking stay has a more negative impact than an equivalent number of 1 or 5 minute stays.
- Nearside road users, buses in particular, are more affected than the rest of the general traffic.
- Nearside lane disruptions increase journey time variability by up to 18% on the surrounding road sections, even in free flow conditions.

Pedestrian facilities

This test analyses the impact of the upgrade of traffic signal pedestrian intergreen from the old standards to TTS6. The previous 'pedestrian to general traffic' intergreen was assumed to correspond to the pedestrian clearance time at a walking speed of 1.2 meters per second. The current TTS6 standard provides more green time for pedestrians. The currently validated VISSIM model complies with TTS6 standards and therefore the VISSIM model has been downgraded to the 1.2 m/s clearance time. The results of this change in pedestrian intergreen time show that:

- The change affects a very limited number of inter-greens.
- The change has a significant impact where it is implemented.
- The economic cost of the inter-greens update depends on the balance between the volume of traffic and the volume of pedestrians and is therefore site specific.

Scenario Comparison

Table 2.2 shows a summary of the tests in terms of economic cost per 1000 vehicles.

Table 2.2: Total cost saving (£ per 1000 vehicles)

Total cost saving (£ per 1000 vehicles)							
	Saturation %	79%	85%	90%	92%	95%	103%
30mph to 20mph speed limit		-53	-41	-50	-51	-35	-78
Long Term Street-works	Street-work 1	-2	-6	-10	-13	-15	-13
	Street-work 2	-13	-17	-13	-18	-19	-24
	Street-work 3	4	-8	-7	-7	-34	-15
	Street-work 4	0	4	3	0	8	-18
	Sum of Individual Street-works	-11	-27	-27	-38	-60	-70
	All street-works	-12	-15	-16	-23	-45	-48
Nearside lane disruption	1 min incident	-11	-13	-16	-23	-19	-4
	5 min incident	-5	-12	-9	-19	-16	-17
	20 min incident	-108	-201	-74	-87	-88	-109
Pedestrian facility	Before to after TTS6 inter-greens	-29	-24	-27	-17	-30	-27

Table 2.3 shows a summary of the tests in terms of economic cost per 1000 trips.

Table 2.3: Total cost saving (£ per 1000 trips)

Total cost saving (£ per 1000 trips)									
	Saturation %	79%	85%	90%	92%	95%	103%	Average	Rank
30mph to 20mph speed limit		-29	-22	-27	-27	-19	-42	-28	2
Long Term Street-works	Street-work 1	-1	-3	-5	-7	-8	-7	-5	8
	Street-work 2	-6	-9	-7	-9	-10	-13	-9	4
	Street-work 3	2	-4	-4	-3	-18	-8	-6	7
	Street-work 4	0	2	2	0	4	-10	0	9
	Sum of Individual Street-works	-5	-14	-14	-19	-32	-38		
	All street-works	-6	-8	-9	-12	-25	-25		
Nearside lane disruption	1 min incident	-6	-7	-9	-13	-10	-2	-8	5
	5 min incident	-3	-6	-5	-10	-9	-9	-7	6
	20 min incident	-58	-108	-40	-47	-47	-59	-60	1
Pedestrian facility	Before to after TTS6 inter-greens	-15	-12	-14	-9	-16	-14	-13	3

Two scenario sets of results sets are not comparable to the others, but with reference to the un-weighted average impact per 1000 trips across all saturation levels in Table 2.3, the four most important individual interventions are as follows:

- The nearside lane disruption (20 minute incident)
- The 30 mph to 20 mph speed limit change
- The pedestrian facility
- The 80 meter street-works

Buses are likely to be more affected than other general traffic by the nearside lane disruption and the economic analysis weighs the impact on buses more heavily than for other modes by virtue of the average loading assumed. The analysis has indicated the complexities of the network interventions and the interpretation of the results.

A more detailed discussion of the results from this study is presented in Appendix A. The drawback of this study is that capacity is analyzed by using the average speeds of vehicles and economic impacts as standards of measure. Absolute value of network capacity under different intervention scenarios, useful for comparing the capacity values is not at all presented.

2.3 Summary

In summary, review of literature revealed that different empirical and simulation methods were used to measure road capacity. Research has been done to analyze capacity using the speed-flow diagram and other empirical methods. But, there has not been much study in capacity prediction, particularly on quantifying the capacity impact of interventions on the overall network. In a few of the simulation based capacity analysis methods previously used, capacity has been determined by increasing the travel demand and recording the maximum throughput. However, such analysis has been limited to link level and no literature was found on application of such methodology in network level.

The next chapter details the methodology and framework to measure network capacity.

Chapter 3

Methodology

This chapter presents a general methodology and framework to measure network capacity. As mentioned in the previous chapter, there has been no independent unit developed to measure the capacity of a network as a whole. Section 3.1 deals with developing a common unit independent of network and type of intervention for measuring capacity. Section 3.2 elaborates the modeling framework detailing the traffic simulator used in this study, the calibration and validation framework including the various goodness-of-fit measures used and finally the framework for measuring network capacity.

3.1 Network Capacity

It is essential to develop a common currency to measure network capacity so that different disruption events and activities on the network can be expressed on a common basis. This would facilitate exploration of traffic impacts in conjunction with a suitable modelling or simulation framework, and would provide a basis for assessing the relative scale or intensity of the different types of intervention.

It could be envisaged that an ordered process for determining the capacity of the network, street-by-street, junction-by-junction (link-by-link, node-by-node) could be constructed. There is, however, a fundamental issue that needs to be addressed. In conventional link-based network analysis, capacity is defined by the maximum number of vehicles (or passenger car units) that can pass a point in a fixed time. Passenger Car Unit (PCU) is a weighted measure for different vehicle types. PCU values for different types of vehicles depend on the various characteristics of the vehicle like its height, length and width. A

car is given a PCU value of 1. Heavy vehicles like buses and trucks have PCU values greater than 1 and two wheelers like bicycles and motorcycles have PCU values less than 1. Such throughput capacity can depend on other flows in the system leading to a ‘non-separable’ problem, and the effective capacity of a network can be limited by that of a bottleneck, where links are connected dynamically by the route pattern. Therefore, summing link capacities is not sufficient to define the effective capacity of a network. For example, consider a hypothetical two link network as shown in Figure 3.1

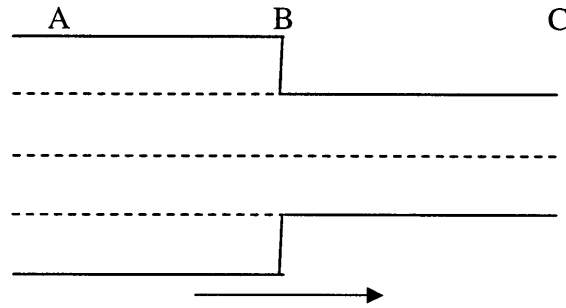


Figure 3.1: Hypothetical network with two links

Link AB with four lanes is connected with a two lane link BC. The direction of traffic flow is from A to C. Here, the capacity of link AB is twice the capacity of link BC. But when the two links are connected together to form a simple network, the overall effective capacity of this network is limited by the bottle-neck at B where the four lanes shrink to two lanes. Hence the effective capacity of this network cannot be equal to the sum of the two link capacities individually.

The number of stationary vehicles that can be physically accommodated in a network (static capacity) is also an insufficient means of determining network capacity as the value of dynamic capacity is of more importance. Nevertheless, both static and throughput capacities contribute to and ultimately determine the effective capacity of the whole network.

Therefore, the following independent unit of measurement for network capacity is proposed in this research. Just as link throughput capacity is definable in units such as

PCUs/hour, the logical measure of network capacity is the amount of travel possible in a given time, i.e. PCU-km/hour. It is the total distance travelled by all the vehicles over a period of one hour. Further, the average speed of the vehicles can be associated with this value of network capacity for better understanding of the impact of various interventions on the network.

In this study, we propose to measure the capacity of a network through a simulation framework by taking a small sized network. A theoretical network capacity can be produced by flooding the model i.e. by changing the scaling factor in the OD matrix. This has been further discussed in detail in the subsequent sections of this chapter.

Thus, it appears feasible to have a method that provides a realistic means of measuring the network capacity and also be able to incorporate into it the impact of interventions that have a detrimental impact on network capacity. The material in this section is based on the TfL report titled “Inventory of Network Capacity and Activity: A Method for Calculating the Capacity of the CCZ”, 2009.

3.2 Modeling Framework

3.2.1 MITSIMLab

MITSIMLab (Yang and Koutsopoulos, 1996) is a simulation-based laboratory that was developed for evaluating the impacts of alternative traffic management system designs at the operational level and assisting in subsequent refinement. Examples of systems that can be evaluated with MITSIMLab include advanced traffic management systems (ATMS) and route guidance systems.

MITSIMLab is a synthesis of a number of different models and has the following characteristics:

- Represents a wide range of traffic management system designs;
- Models the response of drivers to real-time traffic information and controls;

- Incorporates the dynamic interaction between the traffic management system and the drivers on the network.

The various components of MITSIMLab are organized in three modules:

- Microscopic Traffic Simulator (**MITSIM**)
- Traffic Management Simulator (**TMS**)
- Graphical User Interface (**GUI**)

The interactions among the various MITSIMLab modules are shown in Figure 3.2. A microscopic simulation approach, in which movements of individual vehicles are represented, is adopted for modeling traffic flow in the traffic flow simulator (MITSIM). This level of detail is necessary for an evaluation at the operational level. The Traffic Management Simulator (TMS) represents the candidate traffic control and routing logic under evaluation. The control and routing strategies generated by the traffic management module determine the status of the traffic control and route guidance devices. Drivers respond to the various traffic controls and guidance while interacting with each other.

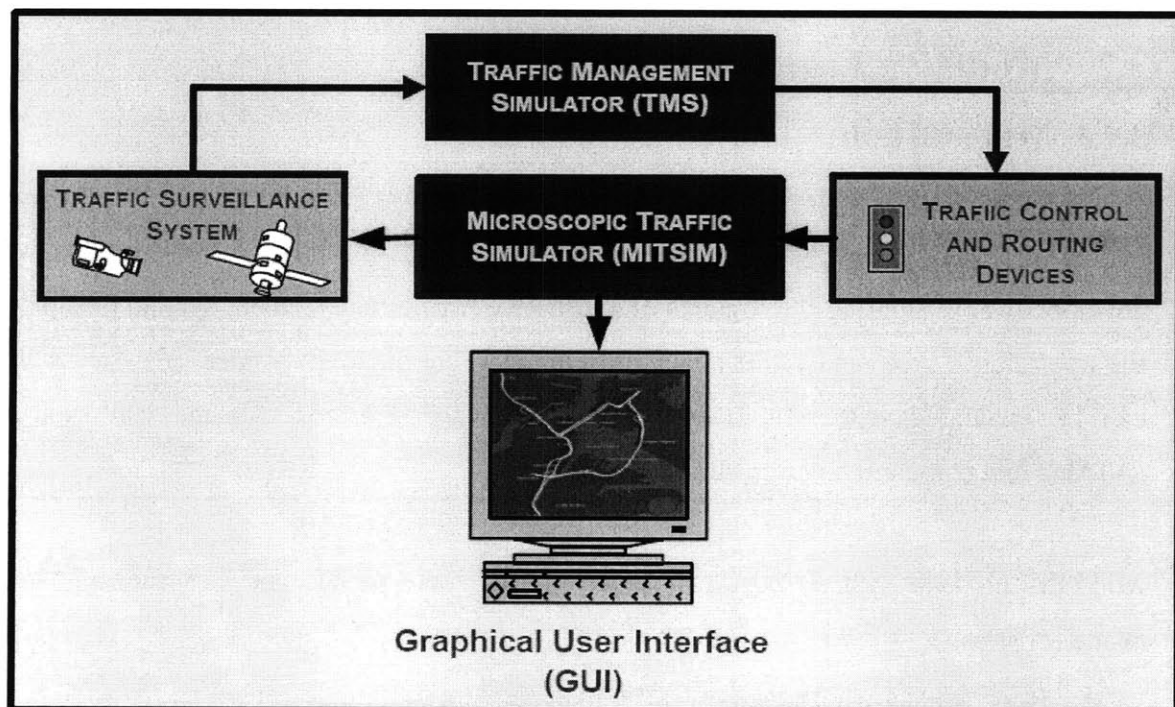


Figure 3.2: Elements of MITSIMLab and their interactions

Traffic Flow Simulator (MITSIM): The role of MITSIM is to represent the “world”. The traffic and network elements are represented in detail in order to capture the sensitivity of traffic flows to the control and routing strategies. The main elements of MITSIM are:

- **Network Components:** The road network along with the traffic controls and surveillance devices are represented at the microscopic level. The road network consists of nodes, links, segments (links are divided into segments with uniform geometric characteristics), and lanes.
- **Travel Demand and Route Choice:** The traffic simulator accepts as input time-dependent origin to destination trip tables. These OD tables represent either expected conditions or are defined as part of a scenario for evaluation. A probabilistic route choice model is used to capture drivers' route choice decisions.
- **Driving Behavior:** The origin/destination flows are translated into individual vehicles wishing to enter the network at a specific time. Behavior parameters (such as desired speed, aggressiveness, etc.) and vehicle characteristics are assigned to each vehicle/driver combination. MITSIM moves vehicles according to car-following and lane-changing models. The car-following model captures the response of a driver to conditions ahead as a function of relative speed, headway and other traffic measures. The lane-changing model distinguishes between mandatory and discretionary lane changes. Merging, drivers' responses to traffic signals, speed limits, incidents, and tollbooths are also captured.

Traffic Management Simulator (TMS): The traffic management simulator mimics the traffic control system in the network under consideration. A wide range of traffic control and route guidance systems can be simulated, such as:

- Ramp control
- Freeway mainline control
- Lane control signs (LCS)
- Variable speed limit signs (VSLS)
- Portal signals at tunnel entrances (PS)
- Intersection control

- Variable Message Signs (VMS)
- In-vehicle route guidance

TMS has a generic structure that can represent different designs of such systems with logic at varying levels of sophistication (from pre-timed to responsive).

Graphical User Interface (GUI). The simulation laboratory has an extensive graphical user interface that is used for both, debugging purposes and demonstration of traffic impacts through vehicle animation.

3.2.2 Calibration Framework

The process of calibration of the simulation system aims to set the various parameters so that observed traffic conditions are accurately replicated. The overall calibration framework is summarized in Figure 3.3.

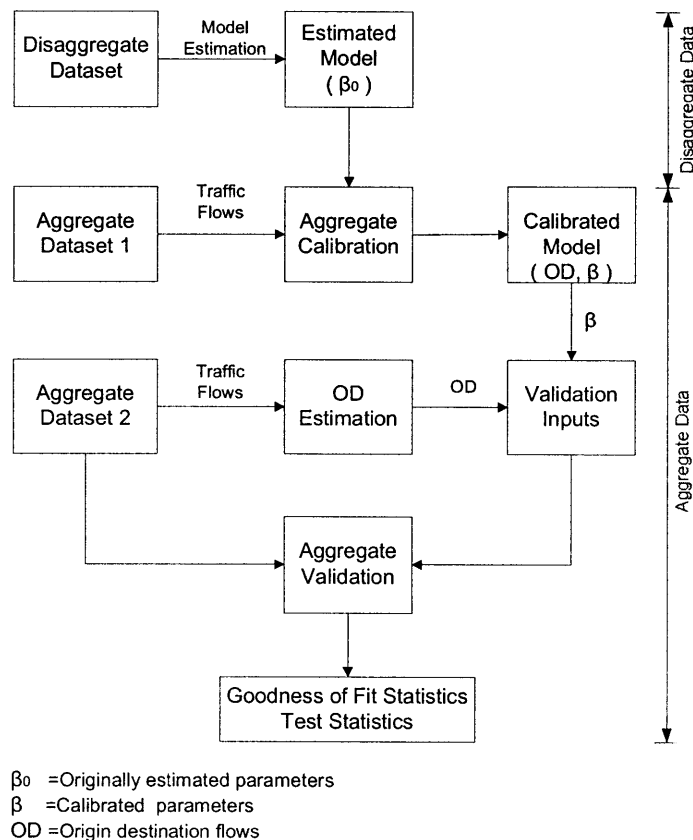


Figure 3.3: Calibration and validation framework

The calibration process consists of two steps: initially, the individual models of the simulation are estimated using disaggregate data. Disaggregate data includes detailed driver behavior information such as vehicle trajectories. The required explanatory variables including speeds and relations between the subject vehicle and other vehicles can be generated from the trajectory data. The disaggregate analysis is performed within statistical software and does not involve the use of a simulation system.

In the second step, the simulation model as a whole is calibrated using aggregate data like flows, speeds, occupancies, time headways, travel times, queue lengths etc. The process of aggregate calibration of the simulation system aims to adjust the various parameters so that observed traffic conditions are accurately replicated. These parameters consist of the parameters of the behavior model (initially estimated parameters β_0 adjusted to β) and the travel demand (expressed in terms of origin - destination or OD flows). Also, in special cases, due to limitations of the available disaggregate dataset it may not be possible to estimate all the parameters of the model in the first step. For example, if the estimation dataset does not have toll lane, it will not be possible to capture the effects of the toll lane-specific variables during the estimation step. In such cases, the values of these omitted parameters can be captured during the aggregate calibration.

Once the calibration is complete, the values of the full set of behavioral parameters are fixed (β) and a second set of data is used for validation. Application of the simulation to replicate this dataset also requires OD flows as input. However, these may be different from the ones obtained in the calibration phase and so the OD estimation component of the calibration must be re-done for this dataset. These new OD flows and the calibrated parameter values are used as inputs to the simulation system.

Problem Formulation

Aggregate calibration can be formulated as an optimization problem, which seeks to minimize a function of the deviation of the simulated traffic measurements from the observed measurements and of the deviation of calibrated values from the a-priori

estimates of the OD flows and the estimated behavior parameters. The formulation presented here assumes that the observations are drawn during a period in which steady state traffic conditions prevail. That is, while OD flows and model parameters may vary for various observation days, these differences are due to random effects and do not represent a change in the underlying distributions of these variables. Furthermore, driving behavior parameters are assumed to be stable over the period of observation. It is important to note that the steady state assumption concerns the variability between observation days, and not within each observation day.

The formulation is shown below. The first and second terms in the objective function are a measure of deviation between observed and simulated measurements and between a priori OD flows and the estimated OD flows respectively. The first constraint shows the dependence of simulated measurements on the driving behavior parameters, OD flows and the network conditions. The second constraint is a non-negativity constraint for the OD flows.

$$\min_{\beta, OD} \sum_{i=1}^N (M^{sim} - M_i^{obs})^T W^{-1} (M^{sim} - M_i^{obs}) + (OD - OD^o)^T V^{-1} (OD - OD^o)$$

$$s.t. \quad M^{sim} = S(\beta, OD)$$

$$OD \geq 0$$

Where,

β = driving behavior parameters

OD = OD flows

OD^o = a priori OD flows

N = number of days for which sensor data is available

M^{sim} = simulated measurements

M_i^{obs} = observed measurements for day i

S = the simulation model function, which generates simulated traffic measurements

W = variance-covariance matrix of the sensor measurements

V = variance-covariance matrix of the OD flows

The sensor measurements in this case constitute of the traffic flows and speeds measurements at all sensor stations and all time intervals.

The formulation presented above is difficult to solve because of the absence of analytical formulations that relate the affect of behavior parameters to the sensor measurements and relatively large number of parameters to calibrate. An iterative solution approach is therefore adopted. In each iteration, first the driving behavior parameters are kept fixed and the OD flows are estimated. Then the OD flows are kept fixed and the driving behavior parameters are estimated.

The number of behavior parameters in the simulation model is very large. It is not feasible to calibrate all of them. A sensitivity analysis is often done to identify the parameters that contribute most in improvement of the objective function. In sensitivity analysis, the impact of an individual factor on the overall predictive quality of the simulator is measured while keeping all other parameters at their original values.

The details of the calibration methodology are presented by Ben-Akiva *et al.* (2003).

3.2.3 Goodness-of-fit measures

Model validation typically includes in it the tasks of aggregate calibration and aggregate validation.

The aggregate calibration process involves adjusting the values of the parameters of the behavioral models and estimating travel demand, in the form of OD flows, on the network being studied in order to obtain a better fit of the model output with the actual traffic flow. The aggregate validation process involves using the calibrated model on a different dataset to determine the extent to which the model accurately replicates traffic behavior.

A number of goodness-of-fit measures can be used to evaluate the overall performance of the simulation model. Popular among them are the root mean square error (RMSE) and root mean square percent error (RMSPE).

The two measures are given by:

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^N (Y_n^{sim} - Y_n^{obs})^2}$$

$$RMSPE = \sqrt{\frac{1}{N} \sum_{n=1}^N \left(\frac{Y_n^{sim} - Y_n^{obs}}{Y_n^{obs}} \right)^2}$$

Where, Y_n^{obs} and Y_n^{sim} are the averages of observed and simulated measurements at space-time point n , calculated from all available data (i.e. several days of observations and/or multiple simulation replications).

RMSE and RMSPE penalize large errors at a higher rate relative to small errors.

Other measures include – Mean Error (ME) and Mean Percent Error (MPE)

ME and MPE indicate systematic under-prediction or over-prediction in the simulated measurements. These measures are given by:

$$ME = \frac{1}{N} \sum_{n=1}^N (Y_n^{sim} - Y_n^{obs})$$

$$MPE = \frac{1}{N} \sum_{n=1}^N \frac{Y_n^{sim} - Y_n^{obs}}{Y_n^{obs}}$$

Where, Y_n^{obs} and Y_n^{sim} are the averages of observed and simulated measurements at space-time point n , calculated from all available data (i.e. several days of observations and/or multiple simulation replications).

3.2.4 Measuring network capacity

Once the model is calibrated and validated, it can be used to find the capacity of a network. The flowchart in Figure 3.4 explains how the capacity of a network is measured in MITSIMLab.

Symbols used in Figure 3.4:

ODF = Scaling factor of OD matrix

UB = Upper bound on the scaling factor of OD matrix

LB = Lower bound on the scaling factor of OD matrix

TOL = Tolerance

The initial value of ODF will be equal to the scaling factor of OD matrix in the calibrated model. Generally, this value is one. The lower bound can be set to zero. Higher values can be used for faster convergence. The value of upper bound should be such that pre-trip queues always form in the network for this value of the scaling factor. The tolerance can be set to 0.01 for all practical purposes. The tolerance can further be lowered depending on the run-time of the simulation.

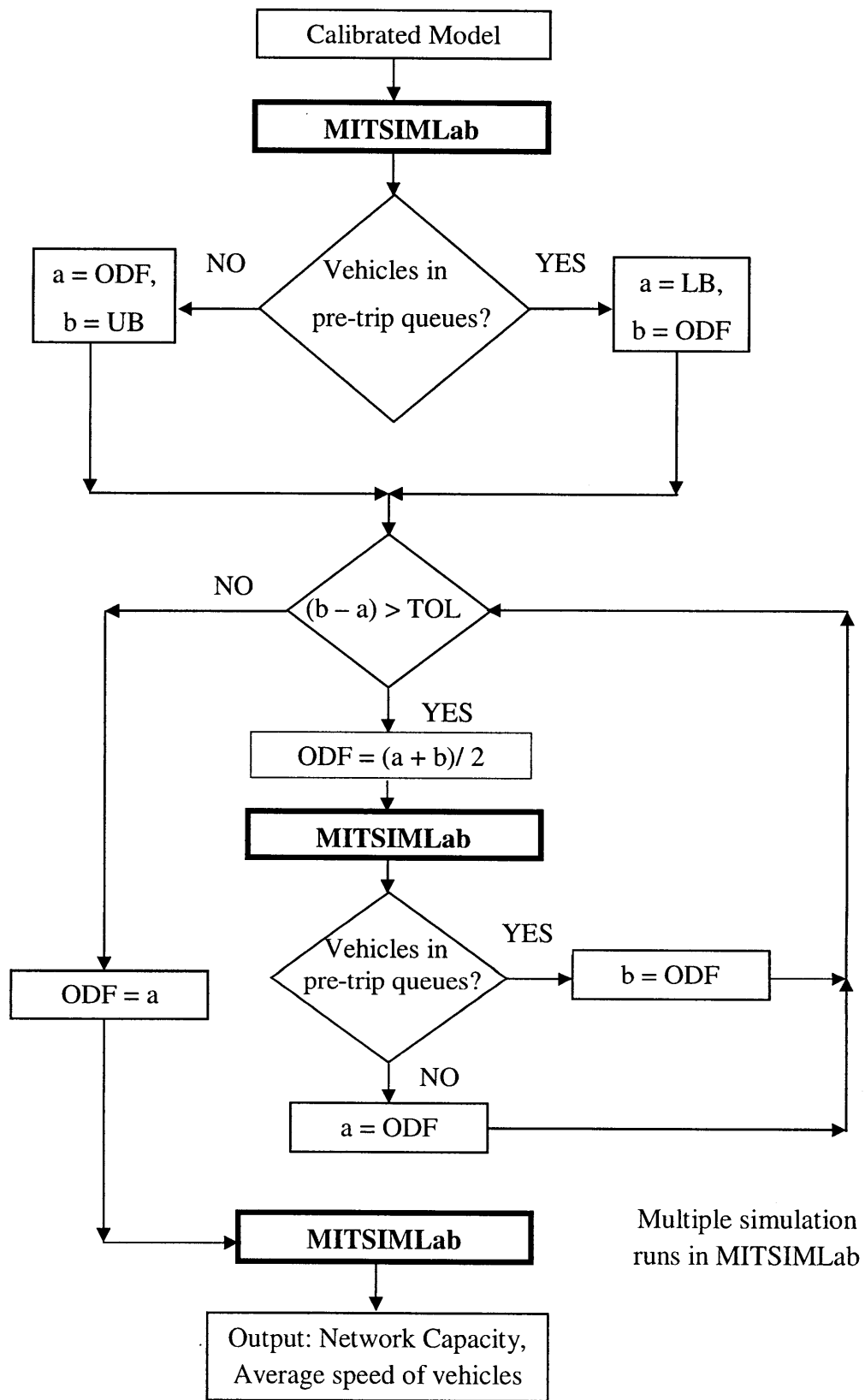


Figure 3.4: Framework for measuring network capacity

In MITSIMLab, the maximum number of vehicles which can be accommodated in the network before ‘pre-trip queues’¹ start forming is denoted as the capacity of the network. Vehicles before entering the simulation are queued up at each and every entry link. Such queues are referred to as pre-trip queues.

The model is run in MITSIMLab with the original OD matrix and the number of vehicles in the pre-trip queues observed throughout the simulation. Depending on the presence or absence of vehicles in the pre-trip queues, the scaling factor in the OD matrix is either reduced or increased and the simulation is run once again. This process is repeated till we reach a scaling factor at which point there are no vehicles in the pre-trip queues and further any slight increase in the scaling factor will result in non-zero vehicles in the pre-trip queues. This is known as “flooding the network”. In MITSIMLab, it is possible to flood the network with just a particular vehicle type. In the current study, the network was flooded with the same vehicle mix as present in the actual network i.e. any change in the scaling factor will correspondingly change the vehicle mix by the same factor. The tolerance for the boundary scaling factors was set to 0.01 in this study. The tolerance can be further reduced for more accurate results, but doing this is much more time consuming. For all practical purposes, this accuracy should suffice. It should be noted that in this study the OD demand was loaded at every 15 minutes and whenever the scaling factor in the OD matrix was changed, the changes were applied for all sets of OD demands simultaneously.

Once the critical scaling factor is found out, the simulation is run multiple times to account for the stochastic models used in MITSIMLab. The outputs from the simulation include the maximum number of vehicles that can be accommodated in the network, the average speed of the vehicles that have reached their destination and the distance travelled by each vehicle from origin node to destination node in the network. After every run these values are recorded and finally the average values of network capacity and speed are reported.

¹ During the simulation, the number of vehicles in pre-trip queues is printed out by MITSIMLab after every minute.

The above framework for measuring network capacity is further clarified through the following example. Consider a calibrated model with the scaling factor of OD matrix (ODF) equal to one. Let the lower and upper bounds of the scaling factors be equal to zero (LB) and four (UB) respectively and the tolerance be equal to 0.01 (TOL). Assume that pre-trip queues form in the network for this value of ODF. Hence $a = 0$ and $b = 1$. Now, assume the following set of iterations (Table 3.1) take place till the scaling factors converge.

Table 3.1: Successive iterations for the scaling factor of an OD matrix

ODF	Vehicles in pre-trip queues	a	b	b-a
0.5	No	0.5	1	0.5
0.75	No	0.75	1	0.25
0.88	No	0.88	1	0.12
0.94	Yes	0.88	0.94	0.06
0.91	No	0.91	0.94	0.03
0.93	No	0.93	0.94	0.01

Therefore the final ODF is equal to 0.93. Using this value of scaling factor for the OD matrix, the simulation is run multiple times in MITSIMLab and the final outputs obtained.

Now, assume that pre-trip queues do not form in the network with the initial value of ODF (equal to one). Using the same values for the bounds and tolerance, we get $a = 1$ and $b = 4$. Assume the following set of iterations (Table 3.2) take place till the scaling factors converge.

Table 3.2: Successive iterations for the scaling factor of an OD matrix

ODF	Vehicles in pre-trip queues	a	b	b-a
2.50	Yes	1	2.50	1.5
1.75	No	1.75	2.50	0.75
2.13	No	2.13	2.50	0.37
2.32	Yes	2.13	2.32	0.19
2.23	No	2.23	2.32	0.09
2.28	No	2.28	2.32	0.04
2.30	Yes	2.28	2.30	0.02
2.29	No	2.29	2.30	0.01

The final ODF is equal to 2.29 in this case. Using this value of scaling factor for the OD matrix, the simulation is run multiple times in MITSIMLab and the final outputs obtained.

3.3 Summary

A general methodology and framework to measure network capacity using a microscopic traffic simulator has been presented in this chapter. Since it is not sufficient to sum the link capacities to find the effective capacity of the network, a common unit independent of network and type of intervention (PCU-km per hour) has been used to measure network capacity. The average speed of the vehicles is also associated with this independent unit.

A general calibration framework and various goodness-of-fit measures have been discussed. In the microscopic traffic simulator MITSIMLab, network capacity is measured by flooding the network with vehicles (i.e. scaling the OD matrix). The network is assumed to reach its capacity when there are no vehicles present in the pre-trip queues. The scaling factor in the OD matrix is changed repeatedly till this condition is

achieved. Finally using this scaling factor, the simulation is run multiple times and the value of network capacity can be calculated.

The next chapter demonstrates the application of this framework on a sub-network from London.

Chapter 4

Case Study: Victoria Network

The previous chapter described the overall modeling framework for capacity analysis. In this chapter, a real network with complex traffic flow patterns has been used to assess the impact of typical network changes on network capacity. A network near the Victoria station area in Central London, U.K. has been used for this purpose. MITSIMLab has been used for calibration and validation purposes and also for capacity analysis.

The chapter is organized as follows: a brief description of the study area and the datasets used is presented in section 4.1. The results of aggregate calibration and aggregate validation are presented in sections 4.2 and 4.3 respectively. Section 4.4 presents the base capacity of this network followed by the capacity analysis under various intervention scenarios in section 4.5. The impact of long term street-works and near-side lane disruptions (illegally parked vehicles) on the capacity of the network has been evaluated in detail in the section dealing with intervention scenarios.

4.1 Dataset description

4.1.1 Study area

The study dataset represents traffic near the Victoria station area located in Central London, U.K. (Figure 4.1). Victoria station is a major central London railway terminus, London underground and coach station in the city of Westminster named after the British monarch Queen Victoria. The network used in this study consists of all the major urban roads around this station. The roads in U.K. are mainly classified into motorways (M-prefix), 'A' roads and 'B' roads (road numbers with prefixes A and B respectively). In Figure 4.1, green colored roads are major 'A' roads, dark yellow or orange colored roads

are minor 'A' roads, light yellow roads are 'B' roads and other local streets are white in color. Motorways (not present in Figure 4.1) are blue in color.

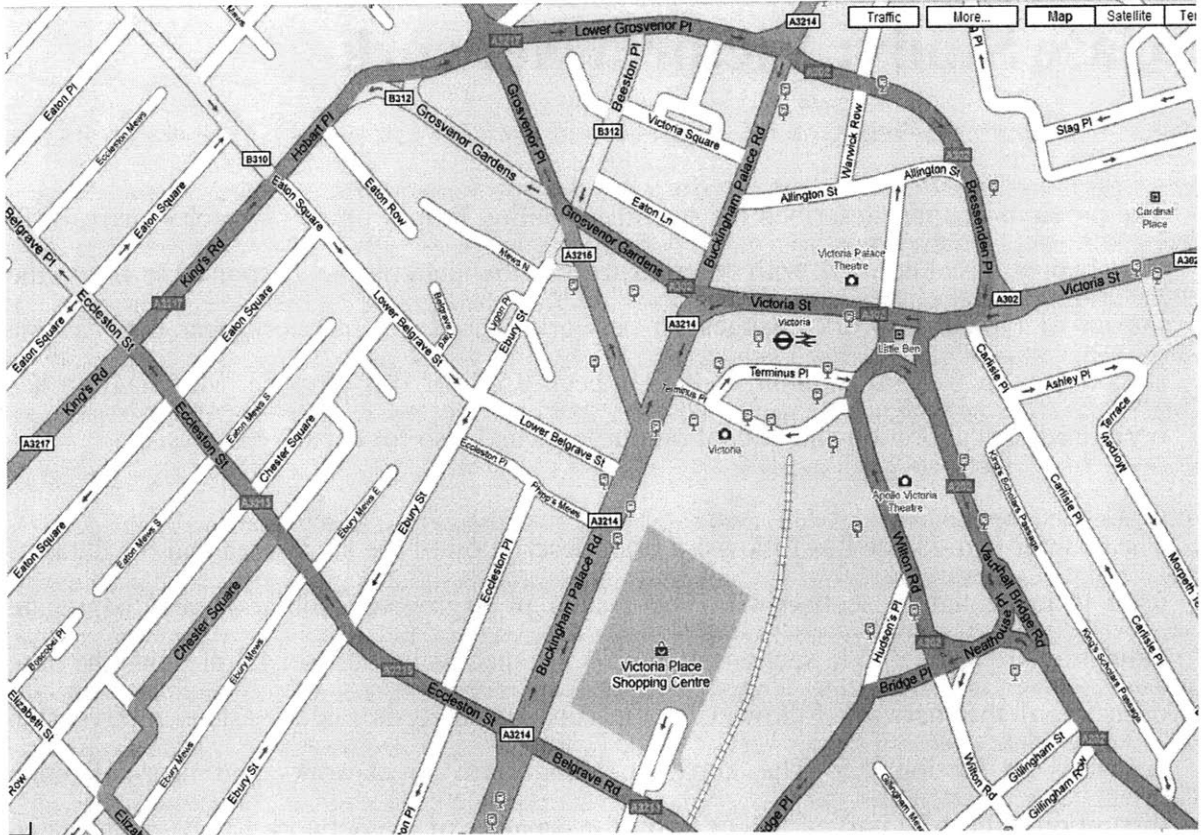


Figure 4.1: Network Description

The computer representation of this network (Figure 4.2) consists of 187 nodes connected by 221 links and 53 signal heads². The actual signal controllers in the field are adaptive. Although MITSIMLab has the ability to simulate the widest possible range of signal controllers, the signals in the network are simulated as pre-timed controllers i.e. the signal states change according to a pre-determined sequence, because the signal timing data that was available could only replicate this type of controller. The MITSIMLab model covers the AM peak period from 7:15 to 9:00 on a week-day.

² A signal head controls one or more traffic-streams that are given right-of-way simultaneously.

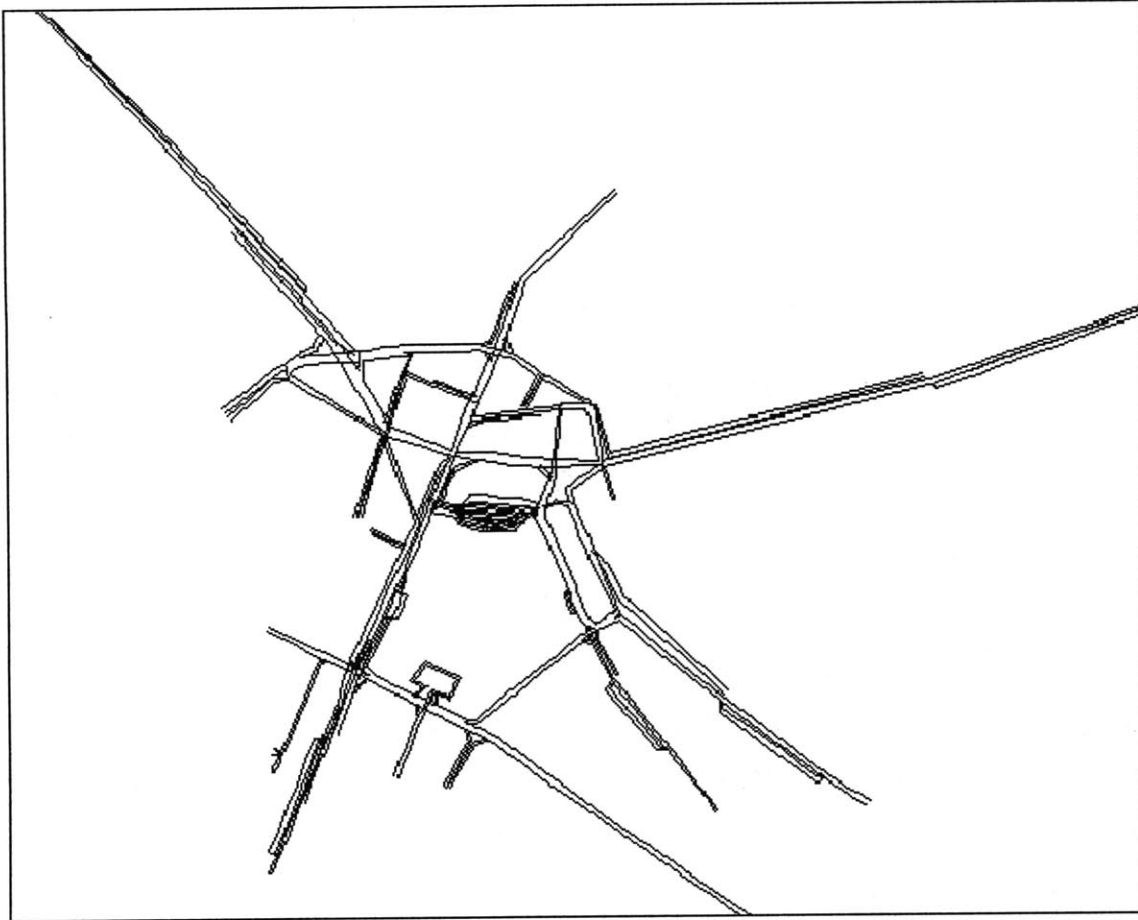


Figure 4.2: Network as seen in MITSIMLab

4.1.2 Dataset overview

Data is collected continuously using Automatic Traffic Counters (ATCs) and Automatic Number Plate Recognition (ANPR) cameras placed at different locations in the network. The ATCs give the counts data while the ANPR cameras give the travel times of vehicles between two points by capturing the license plate numbers at these two points. ANPR and ATC data is available at every 15 minute intervals.

Figure 4.3 shows the location of count and speed sensors in the network.

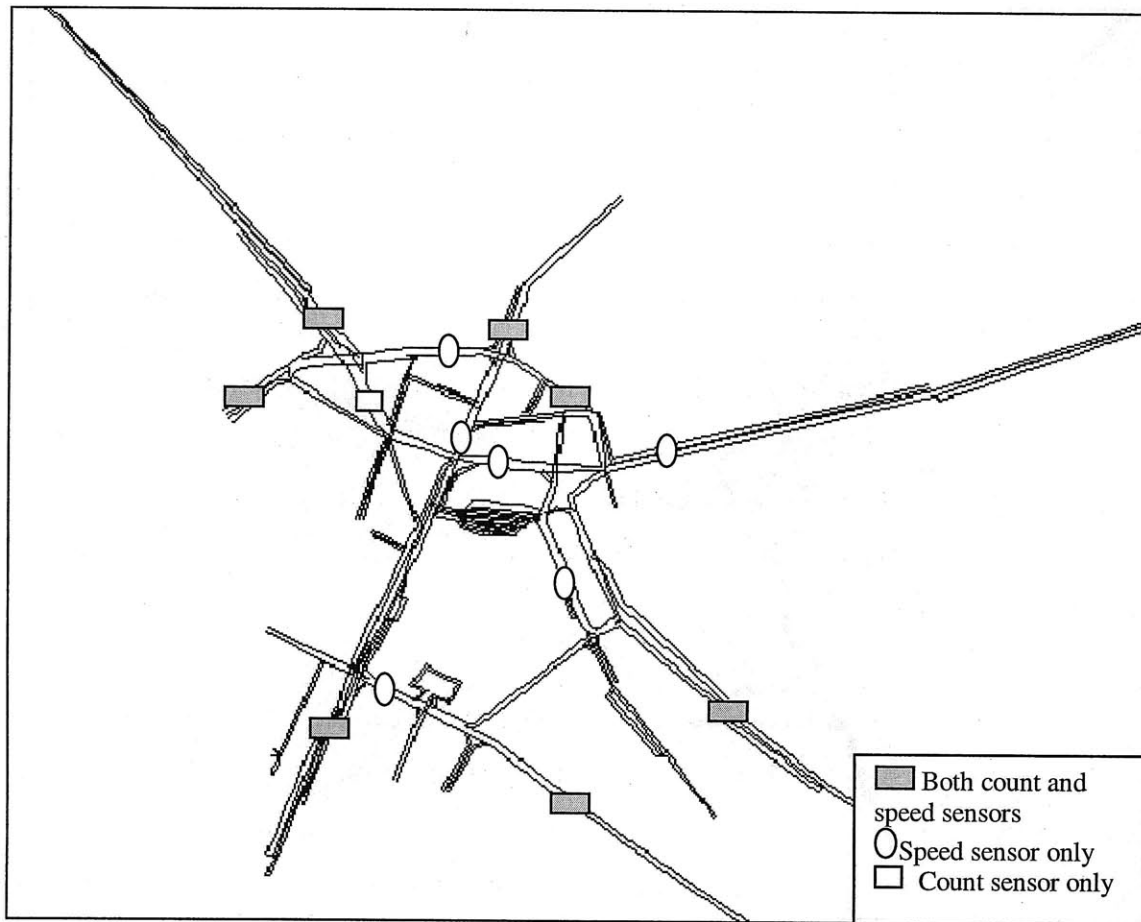


Figure 4.3: Location of sensors

It should be noted that some of the sensors in the network are located on both sides of the road, particularly on those links which serve as entry/exit into the network. On the whole there are 14 sensors each to record counts and speeds at different locations in the network. The statistics for counts and speeds are presented in Table 4.1.

Table 4.1: Statistics of calibration and validation data

Sensor	Average Counts	Average Speeds (km per hour)
1	459	-
2	344	18.02
3	229	18.51
4	50	-
5	160	-
6	75	14.48
7	264	16.25
8	423	-
9	101	23.98
10	103	-
11	79	19.15
12	189	19.79
13	170	-
14	-	11.91
15	-	18.19
16	-	11.91
17	-	11.75
18	-	13.36
19	-	21.40

For the purpose of calibration, ten week-days of data has been used and five week-days of data has been used for validation

4.2 Aggregate Calibration

The calibration problem has been formulated as an optimization problem which seeks to minimize a function of the deviation of the simulated traffic measurements from the observed measurements. The optimization has been done in MATLAB using Box's

complex algorithm. (Box, 1965) A detailed description of the calibration methodology was presented in the previous section.

Based on previous experience, the following parameters have been selected for calibration:

- **Car-following parameters**
 - Acceleration Constant
 - Deceleration Constant
- **Desired Speed**
 - Mean
 - Standard Deviation
- **Critical Gaps**
 - Lead Gap constant
 - Lead Gap standard deviation
 - Lag Gap constant
 - Lag Gap standard deviation
- **Lane Utility Model**
 - Current Lane constant
 - Rightmost Lane constant

Table 4.2 shows the initial and calibrated value of the parameters.

Table 4.2: Calibration results

Parameter³		Initial Value	Calibrated Value
Car following	Acceleration Constant	0.040	0.092
	Deceleration Constant	-0.042	-0.028
Desired Speed	Mean	0.100	0.076
	Standard deviation	0.166	0.473
Critical Gaps	Lead Gap Constant	0.500	2.634
	Lead Gap Standard deviation	1.112	0.596
	Lag Gap Constant	0.500	-0.469
	Lag Gap Standard deviation	0.742	4.864
Lane Utility	Current Lane Constant	4.265	3.706
	Rightmost Lane Constant	0.321	-0.563

The fit of the model to the calibration data is presented in Table 4.3. Although point-to-point travel times were available from ANPR data for this location, goodness-of-fit statistics for travel times are not presented because many of the points (cameras in this case) are located outside the network and hence it is not feasible to compare the travel times in many of the links.

Table 4.3: Goodness of fit statistics for traffic speed comparison

Statistic	Before Calibration	After Calibration	Improvement
RMSPE	1.53	1.38	9.80%
RMSE (m/s)	5.50	5.03	8.54%
MPE	0.94	0.31	67.02%
ME (m/s)	3.45	2.50	27.54%

³ General Parameters used in MITSIMLab. These are described in Ahmed (1999).

As seen from the table, the calibrated model has provided an improved performance when compared with the initial model. But, the values of MPE and RMSPE are very high. This is due to the fact that some of the speed sensors in the network are located on the entry links. This results in large speeds for some of the sensors because the vehicles enter the simulation at high speeds. But the locations of ANPR cameras in the field results in relatively very low speeds for these sensors. Hence, due to the over-estimation of simulated speeds, some of the MOE statistics are very high. Another reason for this difference in simulated and observed speeds can be due to the fact that the signals are simulated as pre-timed controllers (due to the absence of data required for coding adaptive signals), though the actual signal controllers in the field are adaptive.

To account for this over-estimation in simulated speeds, the data from all such sensors where the speeds had been over-estimated were removed and the goodness-of-fit statistics recalculated. The new results are presented in Table 4.4. It can be seen that the values of MPE and RMSPE are far better than those presented in the previous table.

Table 4.4: Corrected Goodness of fit statistics for traffic speed comparison

Statistic	Before Calibration	After Calibration	Improvement
RMSPE	0.27	0.21	22.22%
RMSE (m/s)	5.11	4.29	16.05%
MPE	0.12	0.04	66.67%
ME (m/s)	2.62	2.01	23.28%

4.3 Aggregate Validation

In this step, the calibrated MITSIMLab model is applied on a different set of data to predict the traffic for the validation time-frame.

The fit between simulated and observed traffic in terms of speeds is summarized in Table 4.5.

Table 4.5: MOEs for speeds

RMSPE	1.45
RMSE (m/s)	5.09
MPE	0.91
ME (m/s)	3.33

Similar correction to account for over-estimation of simulated speeds as mentioned in the aggregate calibration section has been applied to generate the corrected MOEs, as shown in Table 4.6.

Table 4.6: Corrected MOEs for speeds

RMSPE	0.23
RMSE (m/s)	4.45
MPE	0.07
ME (m/s)	2.70

4.4 Base Capacity

As mentioned previously, the capacity of the network is measured in terms of PCU-km/hour. It should be noted that all the results presented in this section are in terms of vehicle-km per hour. This is because in the current network, most of the vehicles were cars. Since a car has a PCU value of 1, PCU-km per hour is the same as vehicle-km per hour. If the composition of other heavy vehicles is substantial, then the outputs should be correspondingly converted to PCU values.

The calibrated model is used to find the base capacity of the network. Base capacity is defined as the capacity of the network without any interventions. The base capacity of a network can be affected by a number of actions. These include changes to the configuration of the network like road-works, street-works, incidents and events.

After finding the critical OD matrix, the simulation is run 10 times to obtain average values of the network capacity. The procedure is detailed in section 3.2.4.

Following the steps described in section 3.2.4 for the calibrated Victoria Network, the base network capacity is obtained and is equal to **2754.6 vehicle-km per hour**. The average speed is **24.46 km per hour**.

The next section deals with capacity analysis under different intervention scenarios.

4.5 Scenario Analysis

Long term street-works and near-side lane disruptions are the two interventions which have been analyzed. Both these interventions were simulated by creating an incident in the network at different locations. It was assumed that street-works affect the left-most lane only. Similar tests can be done by closing the right-most lane as well. To find out the network capacity under the various intervention scenarios, the same procedure as mentioned in section 3.2.4 has been used. There will be a drop in network capacity under each of these scenarios.

4.5.1 Long Term Street-works

This test analyzes the impact of various street-works on the capacity of the network. The impact of this change was measured for individual street-works at different locations in the network and different combination of street-works.

In MITSIMLab, street-works have been modeled in such a way that the left-most lane (in the direction of traffic) is completely blocked for traffic movement and the speed limits in the adjacent lanes reduced. The length of street-works is 80m and the interventions were modeled for the whole duration of the simulation. Four different locations of street-works have been chosen.

- Street work 1 is situated on Grosvenor Gardens between Buckingham Palace Road and Beeston Pl. (Figure 4.4)

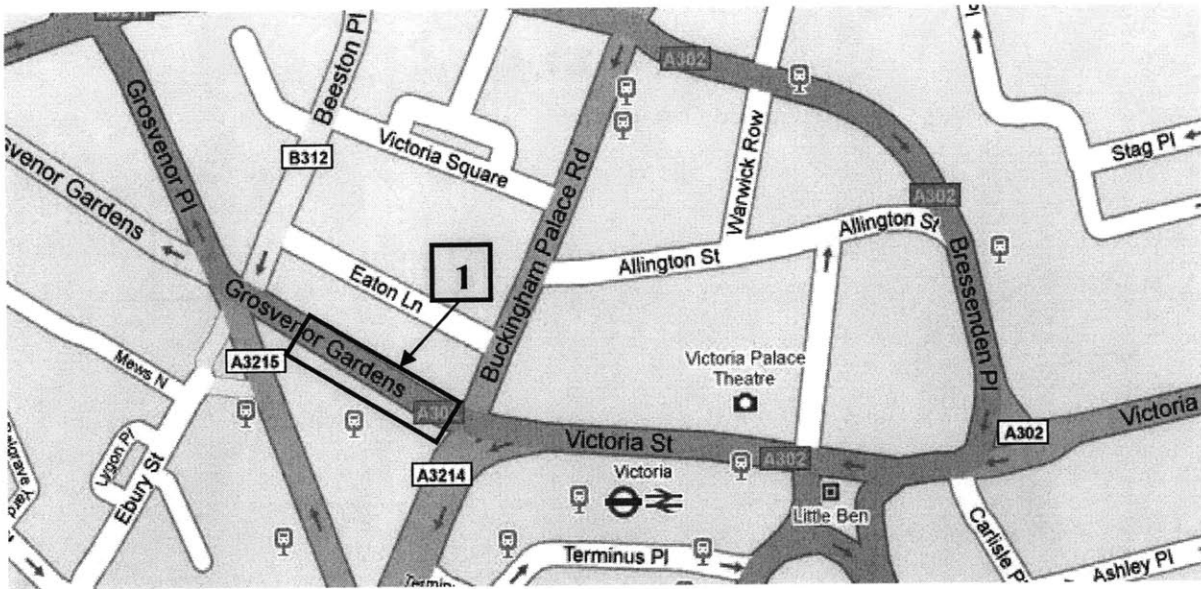


Figure 4.4: Victoria Network – Location of Street-work 1

- Street work 2 is situated on Lower Grosvenor Place between Beeston Pl and Victoria Square (Figure 4.5).

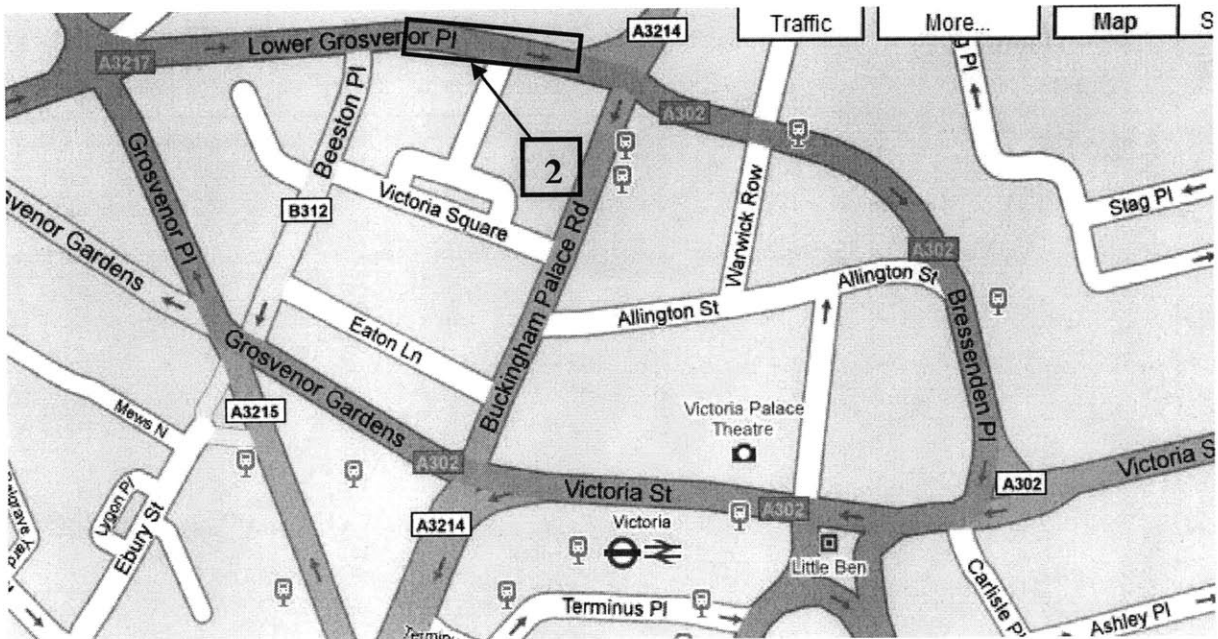


Figure 4.5: Victoria Network - Location of Street-work 2

- Street work 3 is situated on Vauxhall Bridge Road between Victoria Street and Neathouse Pl. (Figure 4.6)

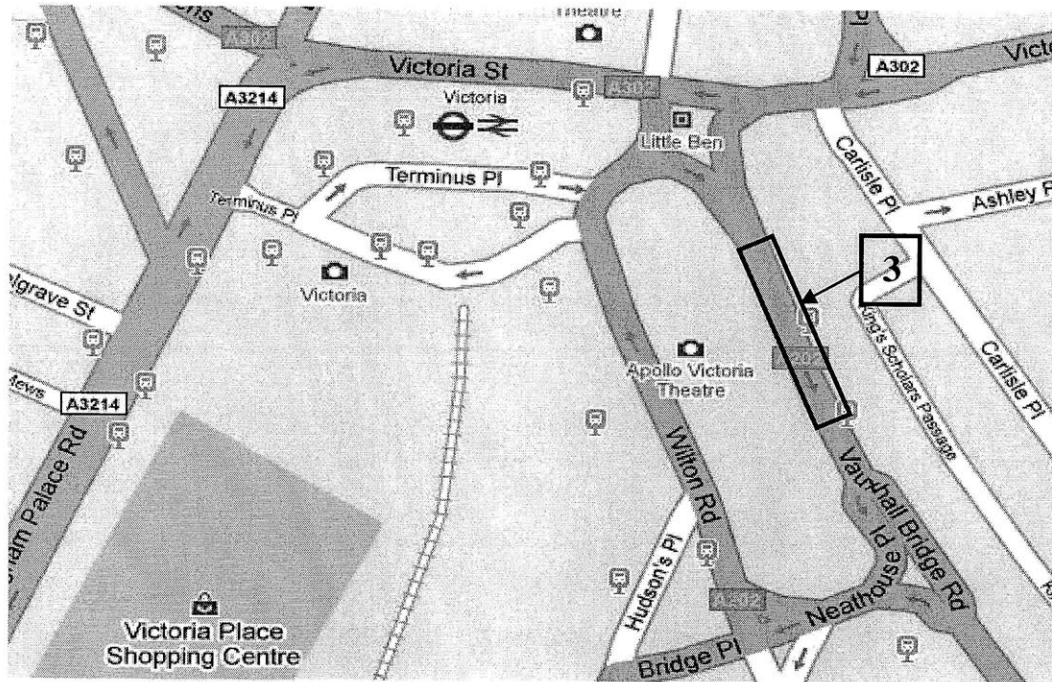


Figure 4.6: Victoria Network- Location of Street-work 3

- Street work 4 is situated on Grosvenor Pl between Beeston Pl and Hobart Pl. (Figure 4.7)

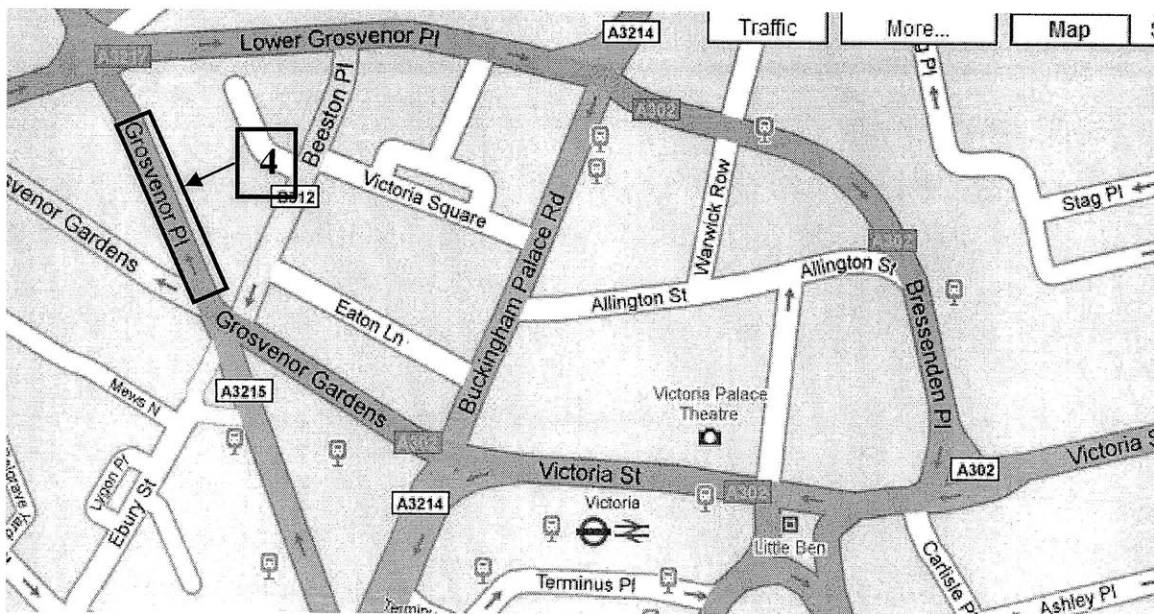


Figure 4.7: Victoria Network – Location of Street-work 4

Capacity Analysis: Individual Street-works

Table 4.7 shows the impact of the four street-works on the overall capacity of the network.

Table 4.7: Street-works – Network Capacity values

Incident	Network Capacity (vehicle-km per hour)	% change from base
Base	2754.6	0
Street-work 1	2387.2	-13.34%
Street-work 2	2592.9	-5.87%
Street-work 3	2288.2	-16.93%
Street-work 4	2485.4	-9.77%

Graph showing the variation of network capacity is plotted in Figure 4.8.

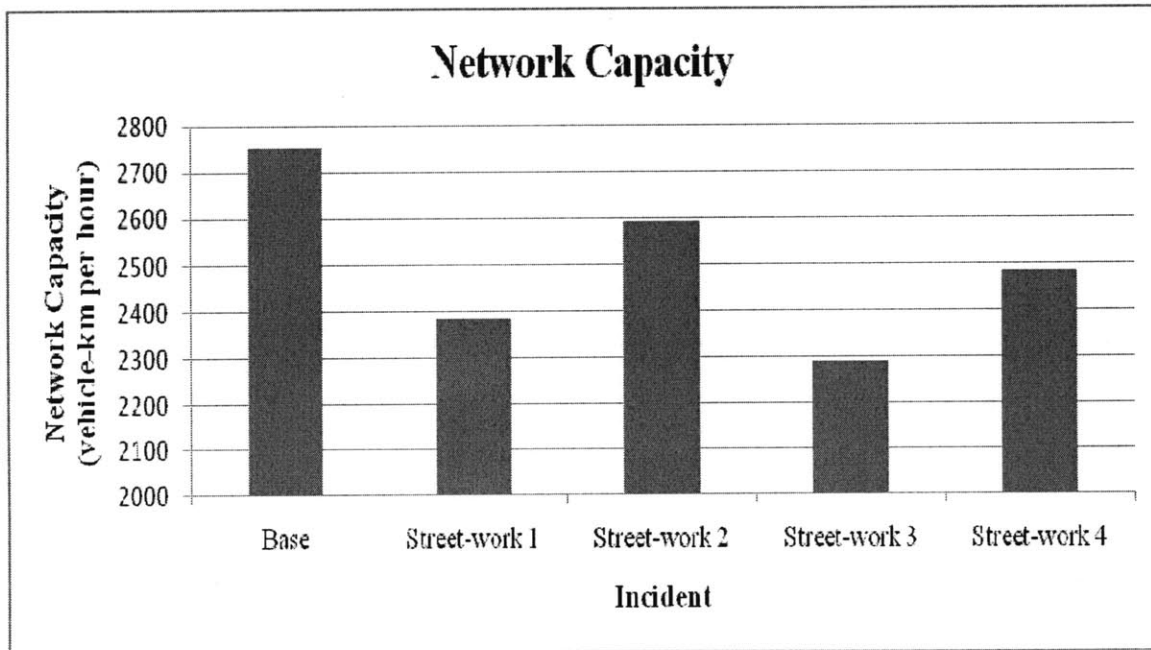


Figure 4.8: Street-works - Network Capacity

Next, the impact of the four street-works individually on the average speed of the vehicles in the network is presented in Table 4.8 and Figure 4.9.

Table 4.8: Street-works – Impact on average speed across the whole network

Incident	Speed (km per hour)	% change from base
Base	24.46	0
Street-work 1	23.66	-3.29%
Street-work 2	24.43	-0.11%
Street-work 3	23.27	-4.87%
Street-work 4	23.71	-3.08%

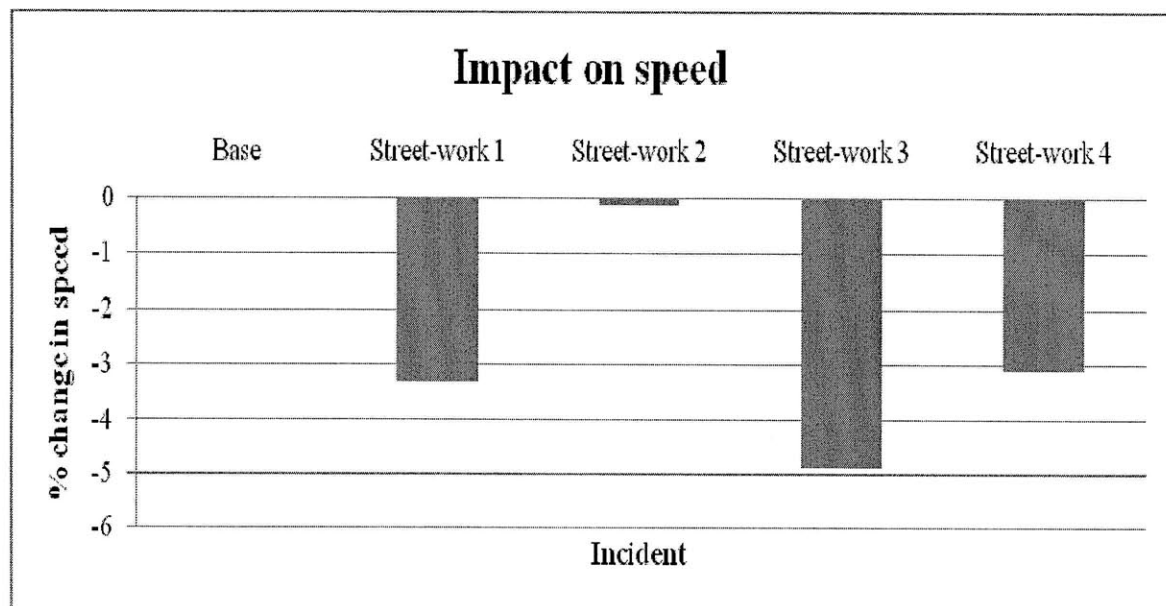


Figure 4.9: Street-works – Impact on speed

The results from Tables 4.7 and 4.8 show that a street-work on an average reduces the capacity of the network from the base case without any interventions by about 11% and the average speed is reduced by about 3.7% (neglecting street-work 2). As mentioned before, a street-work is modeled such that a lane is completely blocked and the speeds on the adjacent lanes are slightly reduced. Further, the street-work is simulated for the whole

duration of the simulation. This has a direct effect on the number of vehicles reaching their destination because the vehicles using that particular link on which a street-work is present will experience fewer lanes and lower speeds and over the course of the simulation it results in a lower number of vehicles reaching the destination compared to the base network. Since the definition of network capacity incorporates the distance travelled by the vehicles reaching their destination, there is a larger reduction in network capacity. Street-works only impact the speeds of the vehicles on the link containing this intervention and probably the upstream link. Hence the reduction in average speed of the vehicles is lower.

Figure 4.10 shows the variation of network capacity with average speed.

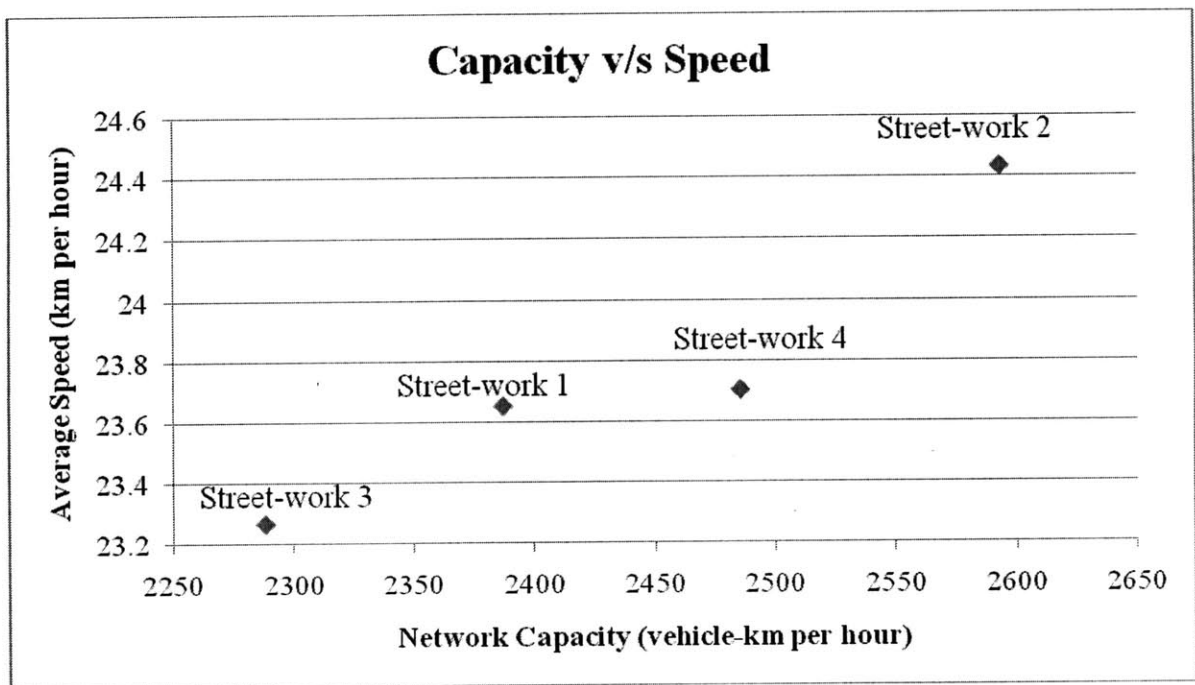


Figure 4.10: Street-works – Capacity v/s Speed

Figure 4.10 shows that there is an approximate linear relationship between network capacity and average speed for individual street-works.

Combination of street-works

To assess the impact of multiple street-works on network capacity, the following three scenarios were chosen:

- Two street-works in the network.
- Three street-works in the network.
- Four street-works in the network.

In the scenario where two street-works are present in the network, street-works at those locations were chosen which caused the highest and second highest reduction in network capacity individually. Hence, in this case locations 1 and 3 were chosen. Similarly for the scenario where three street-works are present, locations 1, 3 and 4 were chosen and in the third scenario, all the four locations were chosen.

Tables 4.9 and 4.10 summarize the impact of street-works on the capacity of the network and the average speed.

Table 4.9: Combination of Street-works – Network capacity values

Incident	Network Capacity (vehicle-km per hour)	% change from base
Base	2754.6	0
Street-work 1	2387.2	-13.34%
Street-work 2	2592.9	-5.87%
Street-work 3	2288.2	-16.93%
Street-work 4	2485.4	-9.77%
Street-work 1+ 3	2274.0	-17.45%
Street-work 1+ 3+ 4	2208.8	-19.82%
Street-work 1+ 2+ 3+ 4	2105.3	-23.57%

Table 4.10: Combination of Street-works – Impact on average speed across the whole network

Incident	Average Speed (km per hour)	% change from base
Base	24.46	0
Street-work 1	23.66	-3.29%
Street-work 2	24.43	-0.11%
Street-work 3	23.27	-4.88%
Street-work 4	23.71	-3.08%
Street-work 1+ 3	24.04	-1.72%
Street-work 1+ 3+ 4	23.00	-5.96%
Street-work 1+ 2+ 3+ 4	22.86	-6.55%

The results from Tables 4.9 and 4.10 show that a combination of street-works causes a greater reduction in network capacity than individual street-works which is intuitive.

4.5.2 Near-side lane disruptions

This test analyzes the impact of near-side lane disruptions on the capacity of the network. The impact of this change was measured:

- For a 1 minute near-side lane disruption every 3 minutes.
- For a 5 minute near-side lane disruption every 15 minutes.
- For a 20 minute near-side lane disruption every 45 minutes.

The near-side lane disruption has been modeled as an on-street parking event with a single-car parked on the nearside lane. To replicate actual parking violations, five different locations on the network were identified using traffic enforcement data. This data contains the exact locations of illegally parked vehicles in the network. It is important to note that the test has been conducted separately for each of the three time-

periods mentioned above and that a parked vehicle was simulated at all the five locations for every time-period.

The locations where near-side lane disruptions have been simulated are mentioned below:

- Disruption 1 is situated on Bressenden Pl. road between Arlington Street and Victoria Street.
- Disruption 2 is situated on Victoria Street between Wilton Road and Buckingham Palace Road.
- Disruption 3 is situated on Vauxhall Bridge Road between Victoria Street and Neathouse Pl.
- Disruption 4 is situated on Grosvenor Gardens between Buckingham Palace Road and Beeston Pl.
- Disruption 5 is situated on Lower Grosvenor Pl. between Beeston Pl. and Buckingham Palace Road.

Figure 4.11 shows the locations of near-side lane disruptions in the network.

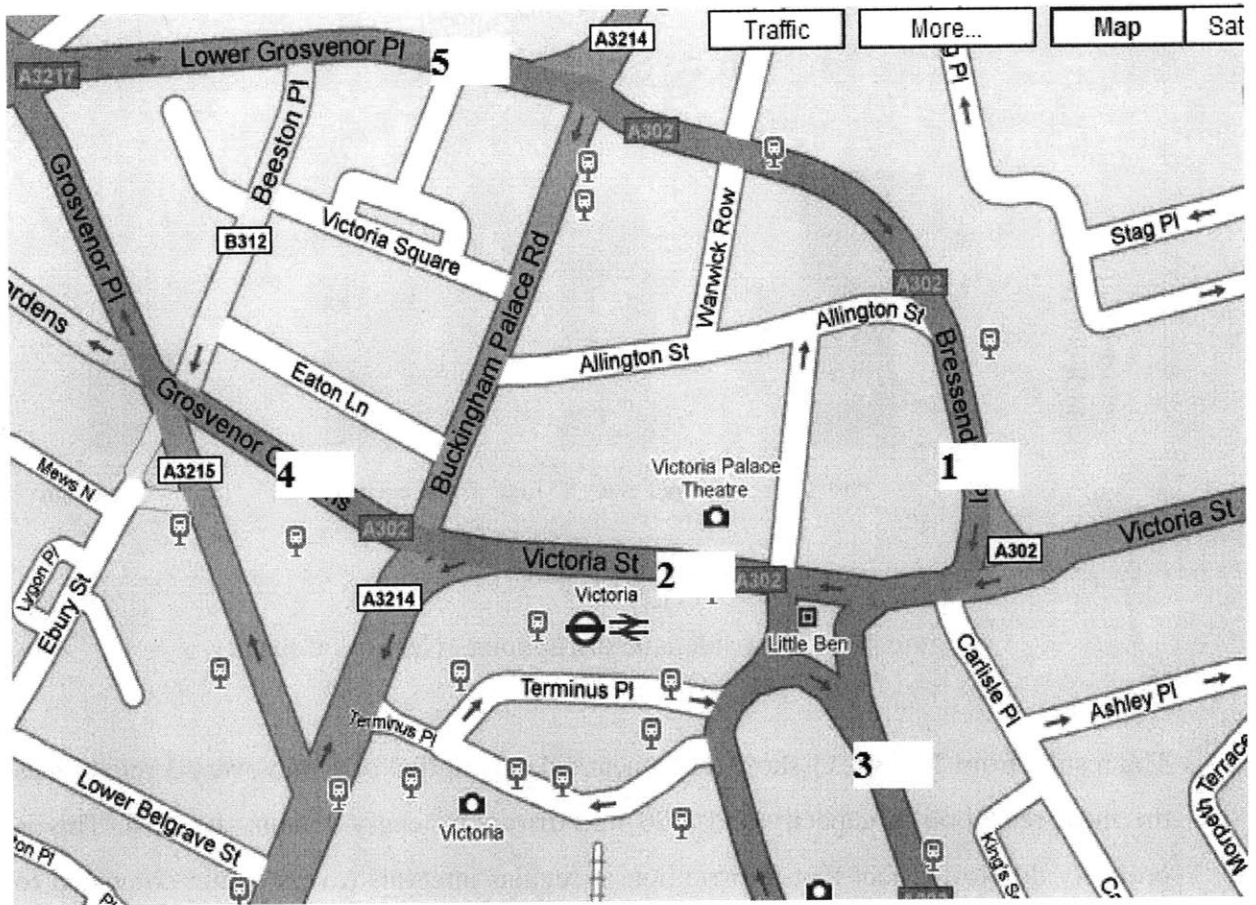


Figure 4.11: Victoria Network - Locations of near-side lane disruptions

Capacity Analysis: Near side lane disruptions

Table 4.11 and Figure 4.12 show the impact of near side lane disruptions on network capacity.

Table 4.11: Near side lane disruptions – Network Capacity values

Incident	Network Capacity (vehicle-km per hour)
Base	2754.6
20 min every 45 min	2711.0
5 min every 15 min	2645.3
1 min every 3 min	2597.4

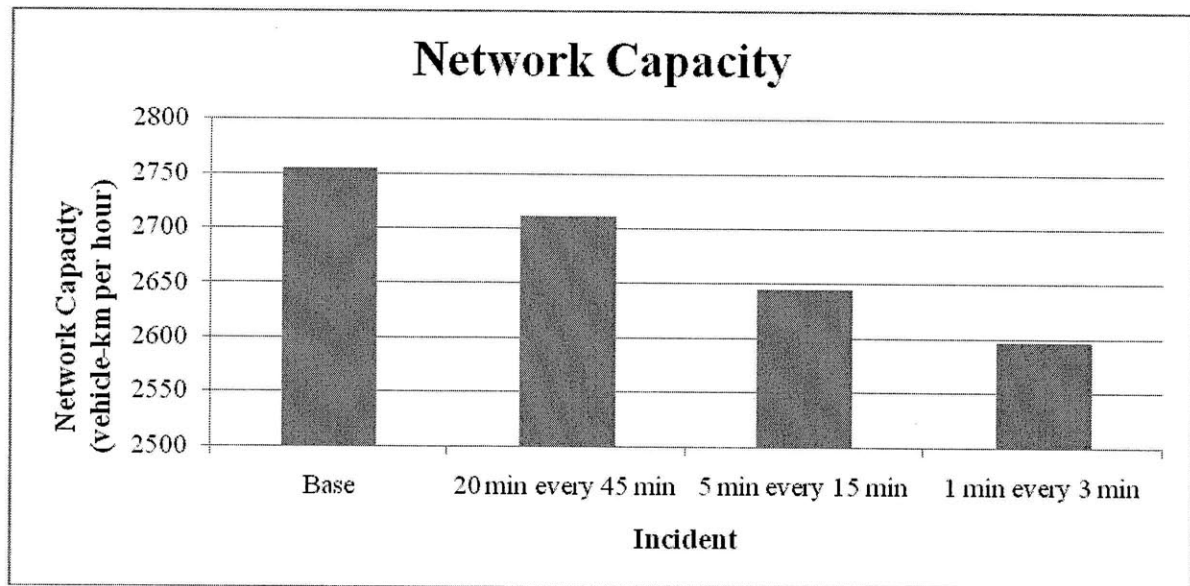


Figure 4.12: Near side lane disruptions - Network Capacity

The results from Table 4.11 show that a near side disruption of 1 min every 3 min causes the most reduction in capacity and a 20 min disruption every 45 min the least. This is probably due to the fact that a disruption at regular intervals (every 3 min compared to every 45 min) will result in a greater instability in the movement of vehicles because the traffic doesn't have enough time to adjust back to 'normal' conditions. Whereas, in the case of a 20 min disruption every 45 min, although the duration of disruption is much longer, the traffic will have more time to adjust back to 'normal' conditions. As we will see later, this also results in a larger reduction in speed for the 3 min interval scenario when compared with the 45 min interval one.

Next, reduction in network capacity due to near-side lane disruptions in the network are presented in Table 4.12 and Figure 4.13.

Table 4.12: Near side lane disruptions – Reduction in network capacity

Incident	% change from base
Base	0
20 min every 45 min	-1.58%
5 min every 15 min	-3.97%
1 min every 3 min	-5.71%

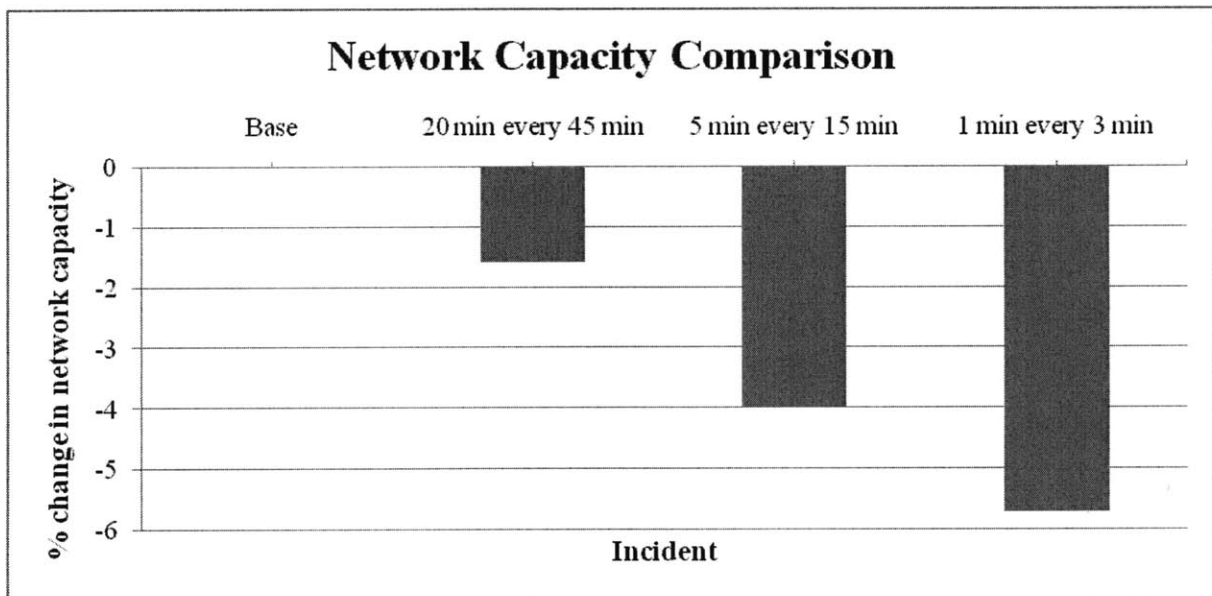


Figure 4.13: Near side lane disruptions - Network Capacity comparison

Comparing the reduction in network capacity due to near side lane disruptions (Table 4.12) with that of street-works (Table 4.7) shows that there is a larger reduction in the capacity of the network in the scenarios where street-works are present. This is because a street-work reduces the width of the road and also affects the speed in the adjacent lanes whereas a near side lane disruption affects only a part of the link and also there is very little effect on the speeds in adjacent lanes.

Next, the impact of near side lane disruptions on the average speed of vehicles in the network is presented in Table 4.13 and Figure 4.14

Table 4.13: Near side lane disruptions – Impact on average speed across the whole network

Incident	Average Speed (km per hour)	% change from base
Base	24.46	0
20 min every 45 min	24.11	-1.44%
5 min every 15 min	23.80	-2.69%
1 min every 3 min	23.72	-3.02%

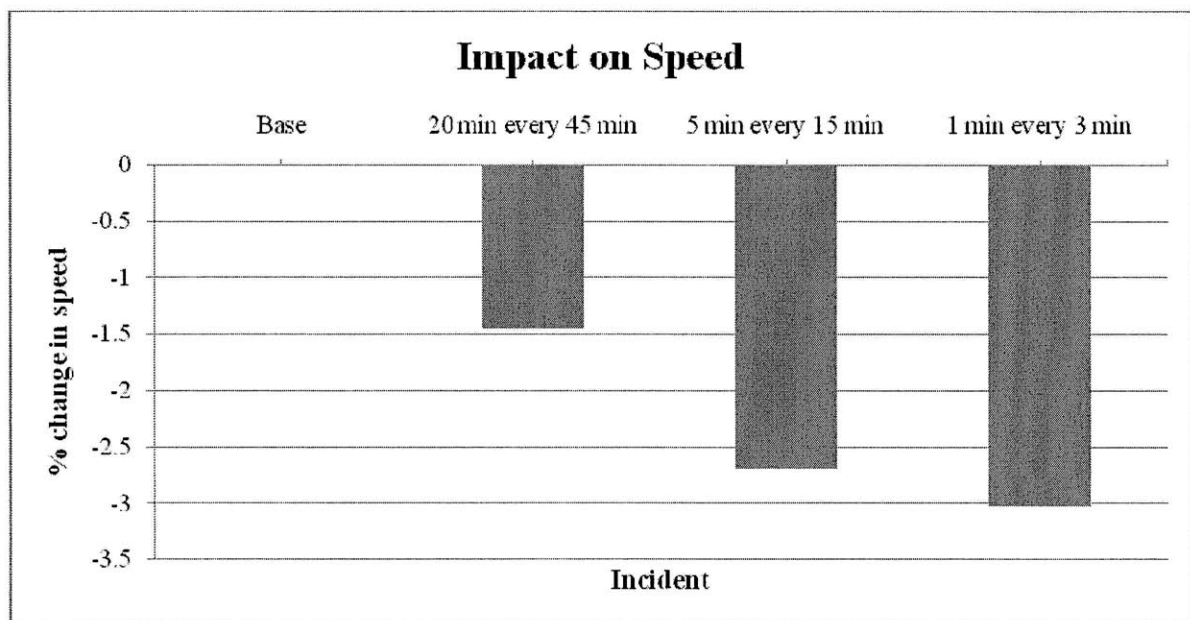


Figure 4.14: Near side lane disruptions – Impact on speed

As expected, the results from Table 4.13 show that a disruption of 1 minute every 3 minutes causes the maximum reduction in average speed.

4.6 Summary

In this chapter the calibration and validation results have been presented followed by the capacity comparisons in different scenarios. The model was calibrated using aggregate speeds and counts data and the goodness-of-fit statistics were satisfactory. This calibrated model was used to find the base capacity of the network without any interventions. Street-works and near-side lane disruptions were simulated to evaluate the impact of these interventions on the capacity of the network.

The results of the capacity analysis of the two interventions using the common capacity currency, predicted a drop in network capacities and average speeds under different scenarios correctly as expected. Street-works resulted in a greater drop in network capacity and average speed than a near-side lane disruption. Further, among the scenarios tested for near side lane disruptions, a 1 minute disruption every 3 minutes caused the greatest reduction in network capacity and average speed.

Chapter 5

Conclusion

5.1 Thesis summary

The main objective of this thesis was to compare capacity changes in sub-networks in various scenarios. The first step was to develop a common unit independent of network and type of intervention to measure capacity and to establish a framework for expressing the capacity impact of the diverse interventions on the network in a consistent manner. There has been little research done in this direction.

In this thesis, we proposed a common unit independent of network and type of intervention to measure capacity. It seemed logical to measure the network capacity in terms of PCU-km/ hour. This is the total distance travelled by all the vehicles over a period of one hour. To measure the network capacity, a simulation framework was adopted. MITSIMLab, a microscopic traffic simulation laboratory developed for evaluating different traffic management systems has been used. In MITSIMLab, network capacity is measured by flooding the network with vehicles i.e. scaling the OD matrix, till 'pre-trip queues' start forming. Vehicles before entering the simulation are queued up at each and every entry link. Such queues are referred to as pre-trip queues. The maximum number of vehicles which can be accommodated now is termed as the capacity of the network. Using the various outputs from the simulation, the network capacity can be measured in terms of PCU-km/ hour.

The modeling framework thus developed to measure network capacity was then applied to an urban network. A network from the Victoria station area in London, U.K was chosen for this purpose. The network represented a typical urban network with many

signalized intersections and complex flow patterns. Using counts and speeds data, the model was calibrated and validated in state-of-the-art microscopic traffic simulation software, MITSIMLab to replicate the local traffic flow behavior.

Once the model was calibrated and validated, capacity analysis was done to evaluate the impact of street-works and near side lane disruptions on network capacity. The average speed of the vehicles reaching their destination was associated with every network capacity value to better understand the variation in speed with network capacity.

First, the base capacity of the network without any interventions was calculated. Next, street-works of 80m length were modeled. Four different locations of the street-works were simulated in the network independently and later in combinations of two, three and four. The results showed that an individual street-work on an average reduced the capacity of the network from the base case by about 11% and the average speed by about 3.7%. The location of street-works also had an effect in the reduction of network capacity and average speed of vehicles. The results from the capacity analysis of the combination of street-works showed a progressive decrease in network capacity and average speed as expected.

Next, near side lane disruptions were modeled as an illegally parked vehicle. Five locations of disruption were chosen in the network. The impact of this intervention was measured for a 1 minute disruption every 3 minutes, a 5 minute disruption every 15 minutes and a 20 minute disruption every 45 minutes. The results showed that a near side lane disruption of 1 minute every 3 minutes caused the greatest reduction in network capacity and average vehicle speed and a 20 minute disruption every 45 minutes the least. Also, the reduction in network capacity in case of a street-work was much larger than in case of a near side lane disruption.

Overall, the results from the capacity analysis were as expected. Thesis contributions and directions for further research are discussed in the subsequent sections.

5.2 Contributions

The thesis develops a framework to measure capacity at a network level. The capacity of the network in the microscopic traffic simulator (MITSIMLab) is measured by flooding the network (increasing the traffic demand) with vehicles. To the best of our knowledge, this is the first time where the flooding approach has been used to analyze the capacity at a network level.

A common unit of measurement has been developed so that the impact of different disruption events and activities on the network can be expressed and compared across scenarios in different networks. Network capacity is measured in terms of PCU-km per hour and the average speed of the vehicles. The unit PCU-km per hour is the total distance travelled by the vehicles reaching their destination over a period of one hour.

A simulation framework has been proposed to quantify the capacity of a network under different intervention scenarios. The feasibility of this framework has been demonstrated by applying it on a sub-network from London. The impact of street-works and near-side lane disruptions (illegally parked vehicles) on network capacity has also been analyzed and the results were as expected.

Expressing the network capacity using this independent unit of measurement will be useful in assessing the relative scale or intensity of the different types of interventions. This will also be helpful in monitoring the capacity of a road network and thereby understand how to manage the supply of physical and effective road capacity. This in turn helps in influencing the road network outcomes such as journey time variability.

5.3 Directions for Future Research

In this thesis, the impact of different disruption events and activities on the capacity of a network has been evaluated through the use of a common capacity currency. There is potential for further research and some of those ideas have been discussed here.

- Link and junction capacity

Link and junction capacities are the basics of understanding how the network behaves and are currently not well understood, especially in terms of their relationship to each other. Understanding the relationship between link, junction and the overall network capacity will be useful for incident analysis. Since the location of disruptions events in both space and time have different impacts on road network capacity, this will be helpful in knowing which are the most important disruption events and activities to manage in order to maintain the highest level of effective network capacity.

- Other hypotheses

In this thesis, the effect of only two non-recurrent congestion causes – street-works and near side lane disruptions (illegally parked vehicles) – on network capacity has been analyzed. But, there might be many more factors which affect road capacity. Some of them are:

- Change in vehicle traffic fleet composition, so that more road space is taken up. This change can be due to the increase in number of buses, heavy goods vehicles (HGV), taxis and private hire vehicles, pedestrians, taxi loading/unloading activity etc.
- Reduction in physical capacity due to the increase in the number of bus lanes, their length and hours of operation, increase in the number and length of cycle lanes, increase in number of advanced stop lines at traffic signals etc.

- Reduction in effective capacity available to road traffic by increasing the number of traffic signals (including changes in cycle timings, addition of pedestrian phases etc) and pedestrian crossings.
 - Mode shift to buses, cycles, walking and other modes of public transport.
- Enhancements of behavior models

In this study, the models used in the simulation were calibrated using aggregate data. But, for more accurate prediction, MITSIMLab needs to be enhanced with improved behavior models estimated with detailed trajectory data that better represent the London traffic. In this case, disaggregate data which includes detailed driver behavior information was not available. It should also be noted that to model some of the factors (e.g. location of advanced stop lines, effect of pedestrian movement etc) mentioned above in MITSIMLab, the source code will have to be improved to better replicate these factors in the simulation.

- Structure of origin-destination (OD) matrix

Considering all the roads within the Congestion Charging Zone in London as part of a large network and observing the number of trips and their trip lengths over a period of time shows that initially as vehicles enter the charging zone, the number of trips with longer trip lengths is more than those with shorter trip lengths. But, after some time it is expected that the number of trips with longer trip lengths decrease whereas the number of trips with shorter trip lengths increase because of an increase in the movement of vehicles inside the charging zone. This affects the average trip length and thereby affects the structure of the OD matrix. This is a limitation which has not been considered in this research.

Appendix A

Detailed Results of A2 Network

A.1 Street-works

This test analyses the impact on the network of various street-works taking place on the carriageway. The impact of this change was measured for:

- Individual street-works at various degrees of saturation
- A final scenario combining all the street-works together

The purpose of the last test was to see if a scenario combining all the street-works has a similar or greater effect compared to the sum of individual street-works. Within VISSIM, the reduction of the number of lanes has been modeled by amending the carriageway to remove the space used by the street-works. This method has the advantage of ensuring that no vehicles can enter the closed area. All the street-works tested correspond to an 80 meters nearside lane closure at 4 different locations. Figure A.1 presents the location of the street-works in the modeled network.

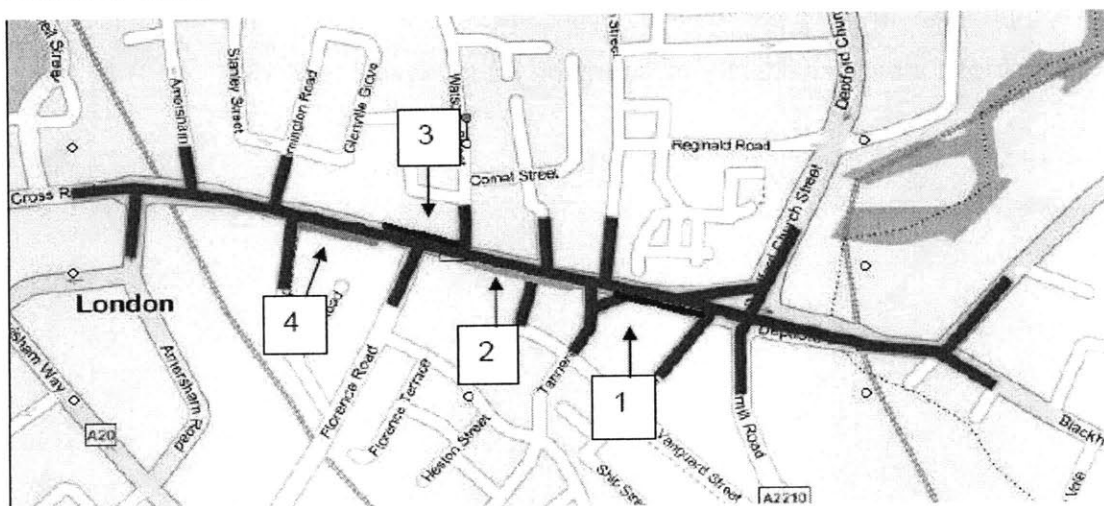


Figure A.1: Street-works locations on the network

Figure A.2 below shows the parts of the network which have been validated against journey time surveys.

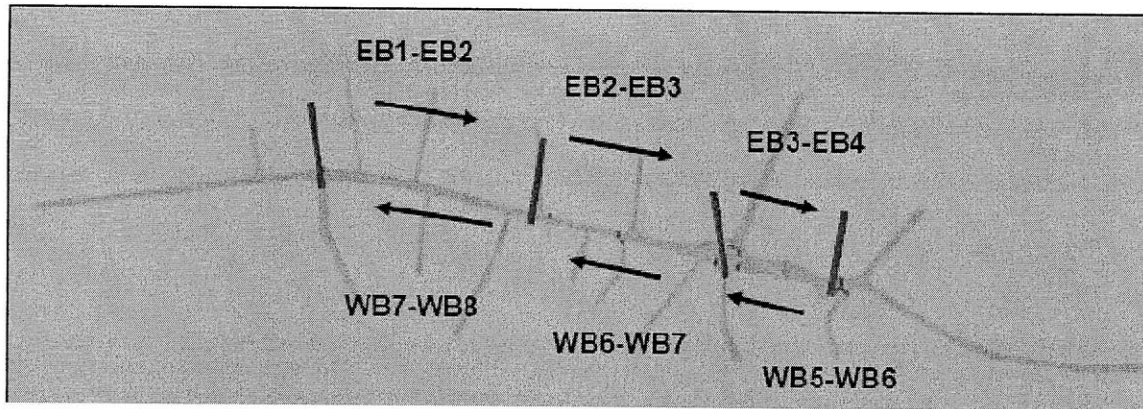


Figure A.2: Journey time sections as surveyed

Network Analysis

The four individual interventions analyzed correspond to:

- the creation of a new merge upstream of an existing merge
- the reduction of a 2-lane carriageway to a single lane by introducing a merge
- closure of a left-turn flare
- street-works closing a bus lane

Table A.1 presents the average vehicle speed under both the base and different street-works scenarios for various degrees of saturation for the whole network.

Table A.1: Street-works average speed summary (mph)

	Saturation (%)					
	79%	85%	90%	92%	95%	103%
Base	11.54	11.37	11.21	11.14	10.83	5.14
Street-work 1	11.54	11.37	11.21	11.06	10.77	5.08
Street-work 2	11.54	11.37	11.21	11.14	10.83	5.11
Street-work 3	11.54	11.37	11.21	11.14	10.79	5.04
Street-work 4	11.54	11.37	11.21	11.14	10.83	5.12
All street-works	11.52	11.35	11.19	11.03	10.42	4.74

Table A.1 illustrates the fact that the individual interventions tested have a very limited impact network-wide. However, the impact of all interventions simultaneously is greater than the sum of individual impacts. The key issue is that while network speeds are low, the levels of saturation generally are quite low as well, and none of the street-works appear to raise saturation levels – they create some additional delay, but not significant congestion. Table A.2 shows the same scenarios as in Table A.1, but indicates percentage differences in speed.

Table A.2: Street-works speed impact summary

	Saturation (%)					
	79%	85%	90%	92%	95%	103%
Street-work 1	0.00%	0.0%	0.0%	0.7%	0.6%	1.2%
Street-work 2	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
Street-work 3	0.0%	0.0%	0.0%	0.0%	0.4%	1.9%
Street-work 4	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
Sum of 4 street-works	0.0%	0.0%	0.0%	0.7%	1.0%	4.1%
All street-works simultaneously	0.2%	0.2%	0.2%	1.0%	3.8%	7.8%

Results in Table A.2 show that the effect of all four street-works taking place simultaneously is twice the effect that would result from the summation of the effect of each individual street-work.

Corridor Analysis

Table A.3 and Table A.4 present the economic analysis results of the street-works test. This identifies a small economic disbenefit for individual street-works in some cases; this may be due to small variations in mode share at the corridor and network level and is not considered a significant disbenefit when considered in the context of the corridor- and network-level changes in speed.

Table A.3: Economic corridor analysis of street-works tests (£ per 1,000 vehicles)

	Saturation %					
	79%	85%	90%	92%	95%	103%
Street-work 1	-2	-6	-10	-13	-15	-13
Street-work 2	-13	-17	-13	-18	-19	-24
Street-work 3	4	-8	-7	-7	-34	-15
Street-work 4	0	4	3	0	8	-18
Sum of individual street-works	-11	-27	-27	-38	-60	-70
All street-works	-12	-15	-17	-24	-47	-46

The results in Table A.3 show that the economic impact of the 4 street-works together is less than the sum of individual street-works within the main corridor. Further checks on the impact per vehicle type do show a relatively uniform impact of the street-works for all vehicle types. This means that most of the delay generated by all street-works occur outside the main corridor, probably upstream eastbound.

Table A.4: Economic corridor analysis of street-works tests (£ per 1,000 trips)

	Saturation %					
	79%	85%	90%	92%	95%	103%
Street-work 1	-1	-3	-5	-7	8	-7
Street-work 2	-6	-9	-7	-9	-10	-13
Street-work 3	2	-4	-4	-3	-18	-8
Street-work 4	0	2	2	0	4	-10
Sum of individual street-works	-5	-14	-14	-19	-32	-38
All street-works	-6	-8	-9	-12	-25	-25

Section Analysis

Table A.5 shows the journey time impact of street-works 1 and 2 for the existing level of traffic demand (100% flow).

Table A.5: Average Journey Time (sec) for street-works 1 and 2

Section	Base	Street - work 1 – new merge			Street - work 2 – 2 lanes reduced to 1 lane		
			Difference	Impact		Difference	Impact
WB5-WB6	82.8	104.6	21.8	26%	105.6	22.8	28%
WB6-WB7	41.7	45.9	4.2	10%	54.1	12.4	30%
WB7-WB8	104	97.5	-6.5	-6%	92.1	-8.3	-11%
Total	228.5	248	19.5	8.50%	251.8	23.3	10%

Table A.5 shows a significant impact upstream of the street-works. The journey time has increased by 10% on the section itself and by 26% upstream of this junction in case of street-work 1. Similarly, street-work 2 creates a situation where the upstream traffic is delayed by approximately 30%. Downstream however, the average journey time has decreased, which means that vehicles are travelling faster. This increase in speed downstream corresponds to the shift of the merging area upstream.

The westbound journey time in the existing situation is 228.5 seconds but becomes 248 seconds when street-work 1 is introduced. The journey time on the section increases by 8.5%, revealing that the traffic flow does not fully recover from the time loss generated by the early merge after the junction. For street-work 2, the time penalty is 23.3 seconds on average.

Table A.6 shows the journey time impact of street-work 3.

Table A.6: Average Journey time (sec) for street-work 3

		Street -work 3 – closure of left-lane flare		
Section	Base		Difference	Impact
EB1-EB2	184.9	217	32.1	17%
EB2-EB3	104.8	90	-14.8	-14%
EB3-EB4	65	64.8	-0.2	0%
Total	354.7	371.8	17.1	4.80%

The results in Table A.6 show that the lane reduction increases the speed of traffic because it forces buses to merge with general traffic. There is no downstream speed impact in this scenario. Interestingly, the time penalty for street-work 3 is 17.1 seconds, which is very close to the results from street-works 1 and 2.

Table A.7 details the journey time impact of street-work 4 which corresponds to a bus lane closure.

Table A.7: Average Journey time (sec) for street-work 4

		Street - work 4 – closure of bus lane		
Section	Base		Difference	Impact
WB5-WB6	82.8	83.8	1	1%
WB6-WB7	41.7	41.7	0	0%
WB7-WB8	104	103	-1	-1%
Total	228.5	228.5	0	0%

The results in Table A.7 show that the bus lane closure has a negligible effect on journey time because the adjacent running lane has spare capacity.

Conclusion

From the figures and analysis above we can conclude that the effect of an individual 80m street-work can be significant at the intervention location. The actual impact depends on:

- The existing saturation level and the future saturation level at that location
- Whether the street-works merely shifts traffic management features (e.g. a merge) from an existing ‘normal’ merge to an upstream ‘street-works’ merge, or is a ‘new’ intervention.

However for the network tested, the effect of any individual intervention is minimal at a network level, provided such an intervention does not make the individual location oversaturated. However when numerous street-works take place at the same time in the same area, their combined effect increases significantly.

A.2 Near side lane disruptions

This test analyses the impact of nearside road disruption on the network operations. The impact of this change was measured for:

- A one minute nearside lane disruption every two minutes

- A five minute nearside lane disruption every ten minutes
- A twenty minute nearside lane disruption every forty minutes.

The nearside lane disruption has been modeled as if it were an on-street parking event. The average time parked per hour in each parking bay is the same throughout the scenarios, but the duration of the stay varies. This test evaluates the impact of nearside lane disruption on buses in particular.

All the road disruptions tested correspond to a single car parked on the nearside lane. The parking was tested concomitantly for each scenario at 4 different locations on the network.

- Disruption 1 is situated on Section WB5-WB6 between Deptford High Street and Deptford Church Street. This location corresponds to a disruption on a merge after a junction.
- Disruption 2 is situated on Section WB6-WB7 between Deptford Broadway and Florence Road. This location corresponds to a disruption on a two lane sections.
- Disruption 3 is situated on Section EB1-EB2 between Alpha Road and Watson's street. This location corresponds to the disruption of the bus lane while the general traffic lane is queuing and at saturation.
- Disruption 4 is situated on Section WB7-WB8 between Alpha Road and Amersham Rd. This location corresponds to the disruption of the bus lane while the general traffic lane is free flowing.

Network Analysis

Table A.8 presents the average speed coefficient of variation for the various types of incidents

Table A.8: Near side road disruption coefficient of variation

Saturation %	Base	Incident 1 min	Incident 5 min	Incident 20 min
103%	7.80%	6.10%	8.20%	23.80%
95%	2.10%	4.70%	1.40%	15.50%
92%	1.10%	2.80%	0.70%	11.60%
90%	1.50%	2.50%	0.80%	12.90%
85%	0.80%	1.80%	0.80%	17.80%
80%	0.80%	1.40%	0.50%	14.50%

Table A.8 shows that the variability of the average speeds on the network for the 1 minute incident and the 5 minute incident scenarios are close to the base case scenario, while the 20 minute scenario shows significant increases over the base. The 1 minute incident scenario experiences more variability, but overall, the scale of the variation is comparable. The 20 minute incident scenario however reflects higher levels of speed variability even at low levels of saturation. The 20 minute incident situation therefore has a major impact on the reliability of network operations.

Table A.9 presents the network disruption speed impact.

Table A.9: Near side road disruptions - speed impact (mph)

Saturation %	Average speed (mph)				% change from base		
	Base	Incident 1 min	Incident 5 min	Incident 20 min	Incident 1 min	Incident 5 min	Incident 20 min
103%	5.19	5.12	5.03	4.87	1.30%	3.10%	6.20%
95%	10.8	9.06	9.75	8.89	16.10%	9.70%	17.70%
92%	11.1	9.72	10.21	9.34	12.40%	8.00%	15.90%
90%	11.2	9.84	10.3	9.46	12.10%	8.00%	15.50%
85%	11.4	10.01	10.42	9.37	12.20%	8.60%	17.80%
80%	11.5	10.27	10.62	9.38	10.70%	7.70%	18.40%

Table A.9 shows an increase in average speed when the traffic conditions become unsaturated. This table also shows that the 5 minute incident has less impact than the 1 minute incident. The reason for this results has not been fully identified, but it could be due to the greater stability of the 5 minutes 'in', 5 minutes 'out' sequence from to the 1 minute sequence – in the former traffic will have more opportunity to adjust back to 'normal' conditions. The drop in average speed is:

- between 0.07 mph and 1.74 mph for a 1 minute incident
- between 0.16 mph and 1.05 mph for a 5 minute incident
- between 0.32 mph and 2.12 mph for a 20 minute incident

Corridor Results

Table A.10 presents the economic analysis of the nearside road disruption test (pounds per 1000 vehicles).

Table A.10: Nearside disruption economic analysis (£ per 1,000 vehicles)

	Saturation %					
	79%	85%	90%	92%	95%	103%
1 min incident	-11	-13	-16	-23	-19	-4
5 min incident	-5	-12	-9	-19	-16	-17
20 min incident	-108	-201	-74	-87	-88	-109

Table A.11 presents the economic analysis of the nearside road disruption test (pounds per 1000 trips).

Table A.11: Nearside disruption economic analysis (£ per 1,000 trips)

	Saturation %					
	79%	85%	90%	92%	95%	103%
1 min incident	-6	-7	-9	-13	-10	-2
5 min incident	-3	-6	-5	-10	-9	-9
20 min incident	-58	-108	-40	-47	-47	-59

Table A.10 shows clearly that the economic impact of the 20 minutes scenario is up to 10 times more significant than the 1 or 5 minutes scenarios. This conclusion probably arises from the fact that buses are using the nearside lane and that this transport mode is particularly affected by the nearside lane disruption. Table A.11 presents a similar trend, but the cost per trips is approximately half the cost per vehicles, as per the previous scenarios.

Section Results

Table A.12 presents the average speed on the network per direction per scenario.

Table A.12: Nearside road disruption average speed per section (mph)

	Saturation %					
	79%	85%	90%	92%	95%	103%
Eastbound 1 min	12	11.5	11.2	10.7	9.9	5.3
Eastbound 5 min	12	11.4	11.2	10.8	9.7	5
Eastbound 20 min	11.5	10.5	11.2	10.9	9.9	5.3
Westbound 1 min	10.8	10.6	10.3	10.3	9.7	7.8
Westbound 5 min	11.1	10.8	10.6	10.4	10.1	8.1
Westbound 20 min	7	6	7.9	7.8	7.7	6.1

Table A.12 shows clearly that most of the impact on the network occurs westbound, the non-saturated direction, compared to on the congested eastbound direction. This configuration and the fact that there were three disruptions westbound as opposed to 1

eastbound created a larger impact westbound, despite the low level of saturation. In fact, the low level of saturation might have been an aggravating factor, as vehicles are travelling at higher speed, and could find it more difficult to find a gap to overtake the parked vehicle.

Conclusion

The nearside lane disruption shows that:

- A 20 minute parking stay has a more negative impact than an equivalent number of 1 or 5 minute stays.
- Nearside road users, buses in particular, are more affected than the rest of the general traffic.
- Nearside lane disruptions increase journey time variability by up to 18% on the surrounding road sections, even in free flow conditions.

Bibliography

Ahmed, K. I. (1999), "Modeling drivers' acceleration and lane changing behaviors", PhD thesis, *Department of Civil and Environmental Engineering, MIT*.

"AIMSUN 6.1 Micro simulator User manual", (2009), Transportation Simulation Systems, Barcelona, Spain.

Box, M. J. (1965), "A New Method of Constrained Optimization and a comparison with other methods", *Computer J.* 8, pp. 42-52.

Brilon, W. (2000), "Traffic Flow Analysis beyond Traditional Methods", *Proceedings of the 4th International Symposium on Highway Capacity*, pp. 26-41, *TRB Circular E-C018, Transportation Research Board, Washington D.C.*

"CORSIM User's Guide, Version 6.0", (2006), FHWA, U.S. Department of Transportation, Washington D.C.

FGSV, (2001), *Handbuch fuer die Bemessung von Strassenverkehrsanlagen (German Highway Capacity Manual)*. Forschungsgesellschaft fuer Strassen- und Verkehrswesen, Cologne.

Geistefeldt, J (2008), "Empirical relation between stochastic capacities and capacities obtained from the speed-flow diagram", *Proceedings of the Symposium on the Fundamental Diagram: 75 years*, Woods Hole, MA, July 8 -10.

Hadi, M. A., Sinha, P. K., and Wang, A. (2007), "Modeling Reductions in Freeway Capacity due to Incidents in Microscopic Simulation Models", *In Transportation Research Record: Journal of the Transportation Research Board*, No. 1999,

Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 62–68.

“Highway Capacity Manual (HCM)”, (2000), Transportation Research Board, National Research Council, Washington D.C.

Hyde, T. and Wright, C. C. (1986), "Extreme value methods for estimating road traffic capacity", *Transportation Research Part B: Methodological, Elsevier, vol. 20, No.2, pp. 125-138.*

Jha, M. (1998), “Analysis of the impact of freeway bottlenecks and a paradox”, *Draft Paper*

Jha, M., Bierlaire, M., (1998), “Capacity at freeway bottlenecks: A simulation study”, *Draft Paper*

Minderhoud, M. M., Botma, H., and Bovy, P. H. L. (1997), “Assessment of Roadway Capacity Estimation Methods”, *Transportation Research Record No. 1572, pp. 59-67*

Minderhoud, M. M. and Bovy P. H. L. (1999), “Impact of Intelligence Cruise Control on Motorway Capacity”, *Transportation Research Record No. 1679, pp. 1-9.*

Schrank, D. and Lomax, T. (2009), “The 2009 Urban Mobility Report”, *Texas Transportation Institute, The Texas A&M University System.*

Transport for London, (2007), "Annual Report and Statement of Accounts 2006/07, April 2007"

Transport for London, (2007), "Central London Congestion charging - Impacts monitoring - Fifth Annual Report, June 2007"

Transport for London, (2008), "Central London Congestion charging - Impacts monitoring - Sixth Annual Report, July 2008"

Transport for London, (2009), "Impact of Interventions on Road Capacity in London", London

Transport for London, (2009), "Inventory of Network Capacity and Activity: A Method for Calculating the Capacity of the CCZ", London

"VISSIM Version 5.2 Manual", (2009), PTV Planug Transport, Verkehr AG. Karlsruhe, Germany.

Yang, Q. and Koutsopoulos, H., N. (1996), "A microscopic traffic simulator for evaluation of dynamic traffic management systems". *Transportation Research 4C*, pp. 113-129.